Short-baseline $\bar{\nu}_\mu \to \bar{\nu}_e$ Oscillation Search with the NuMI Off-axis Beam

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Short Baseline Neutrino Workshop, FNAL

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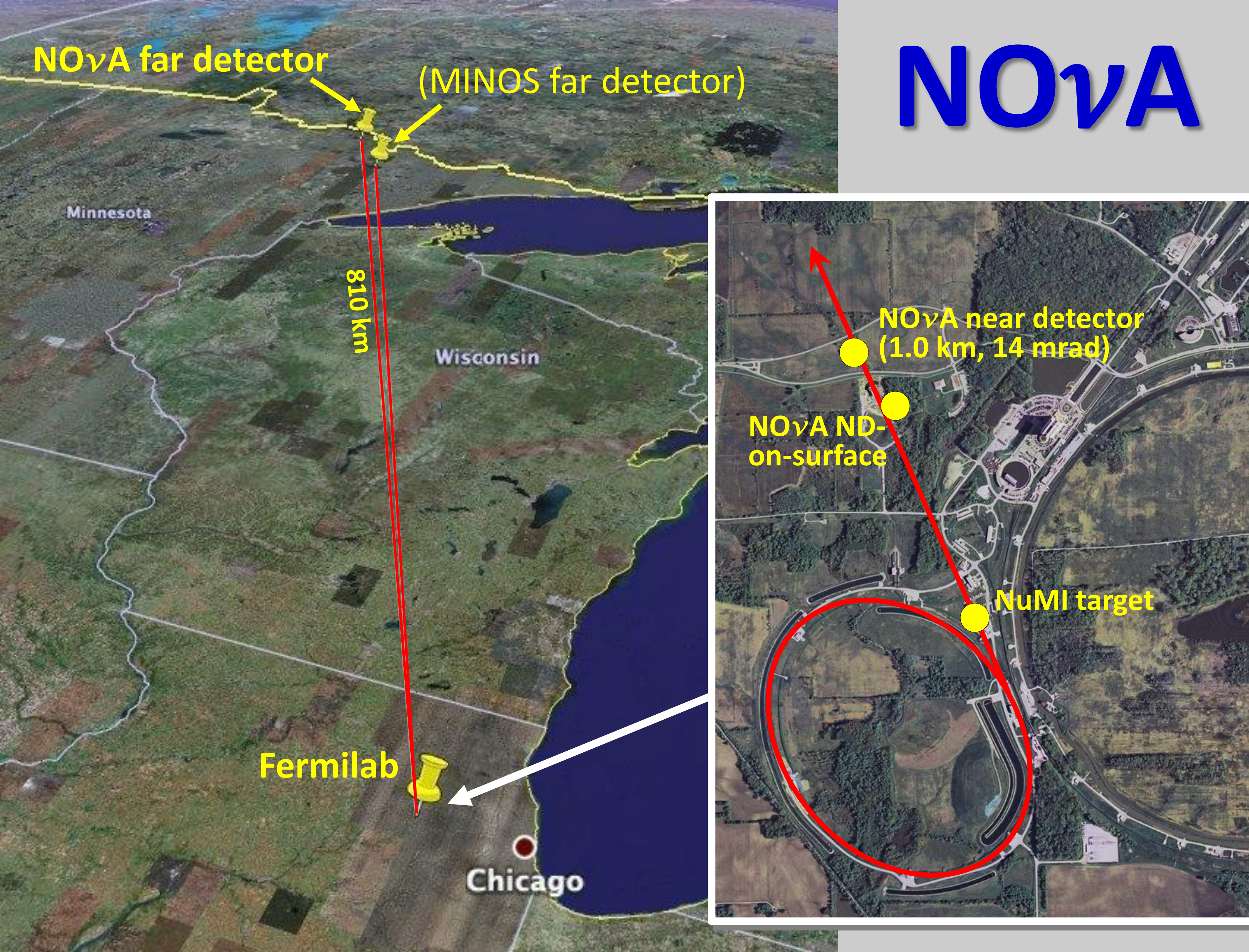
* for Ryan Patterson and Mark Messier

NOνA



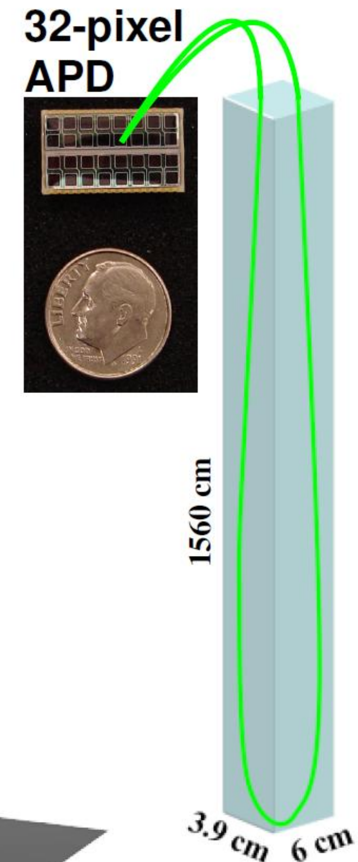
NOνA far detector
(MINOS far detector)
Minnesota
810 km
Wisconsin
Fermilab
Chicago
NOνA near detector
(1.0 km, 14 mrad)
NOνA ND-
on-surface
NuMI target

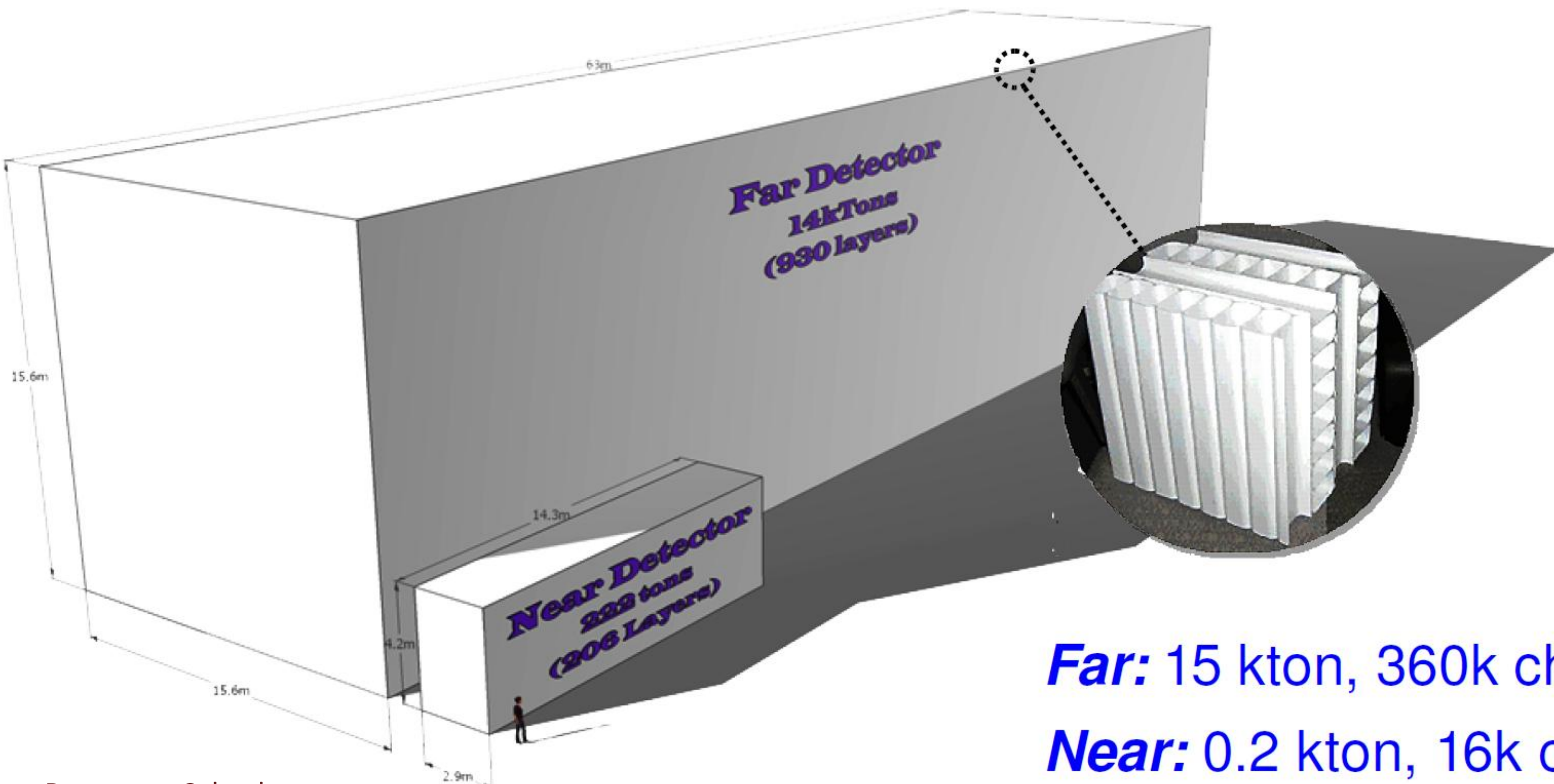
NOνA detectors:

Designed for **excellent ν_e CC identification**

Fine-grained readout, low-Z materials, 80% active volume

- planes of **4 cm** x **6 cm** x **1560 cm** PVC cells
- cells filled with **liquid scintillator**
- readout by **WLS fiber** / **avalanche photodiode**

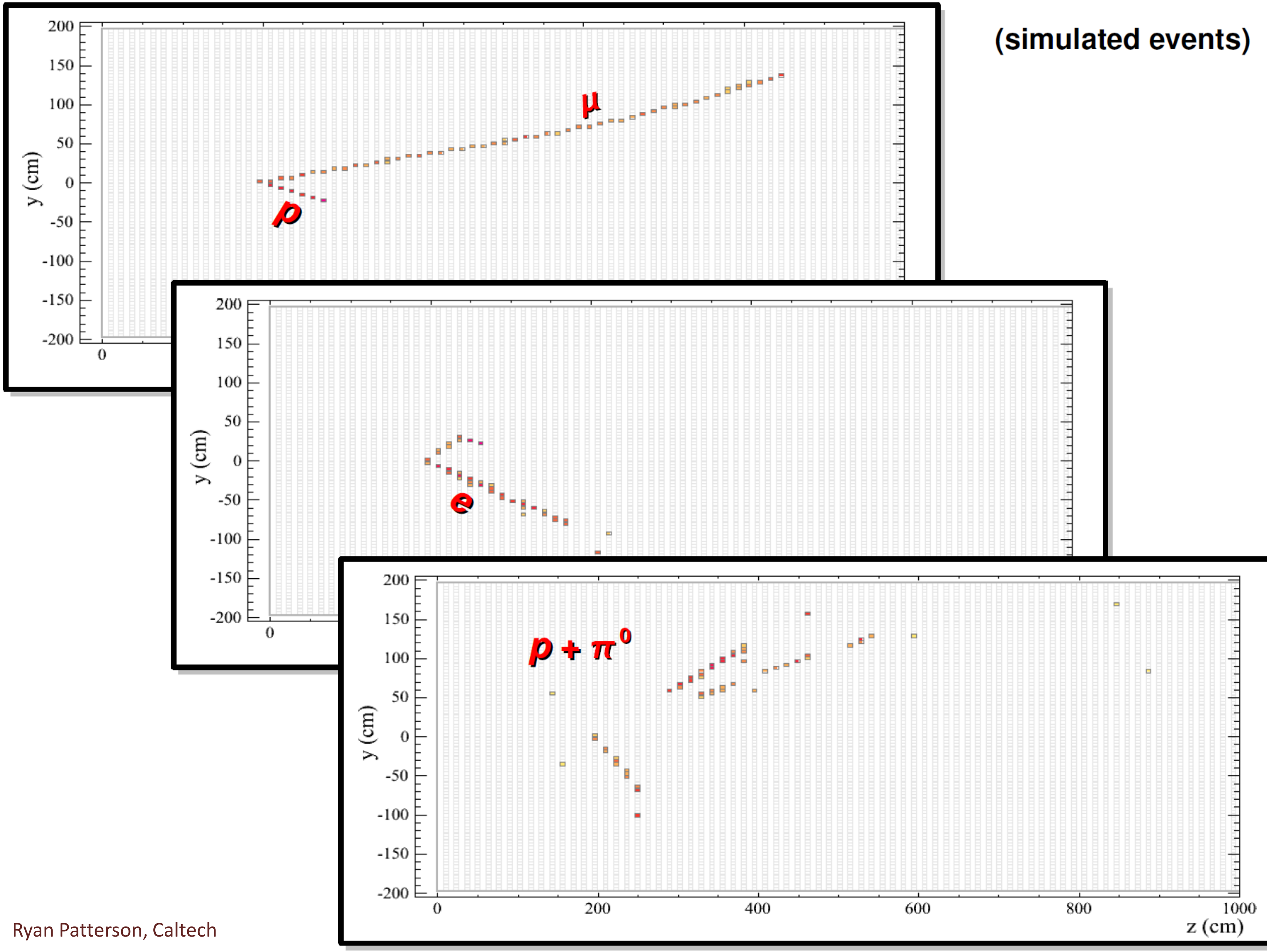




Far: 15 kton, 360k channels

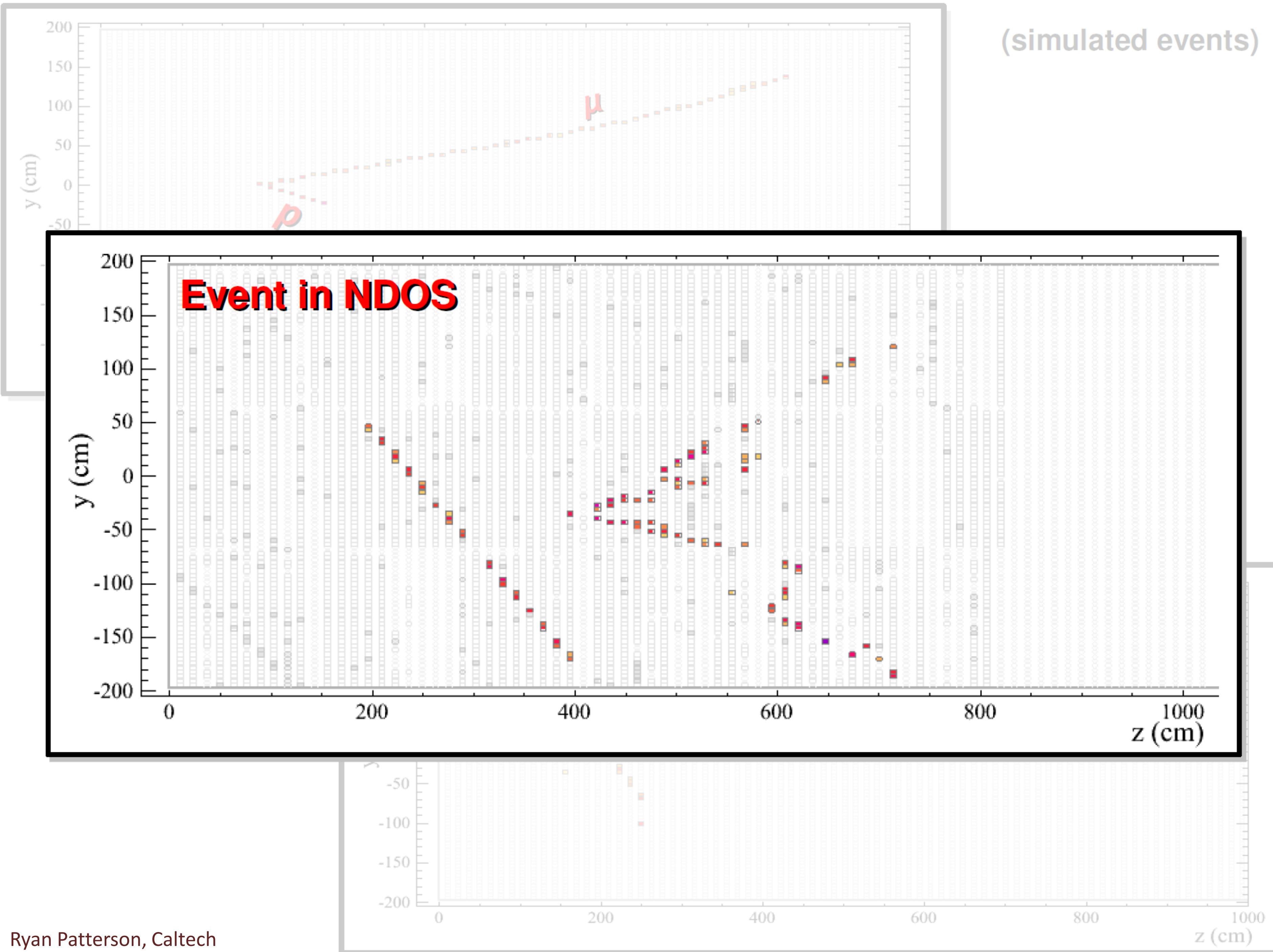
Near: 0.2 kton, 16k channels

(simulated events)



Ryan Patterson, Caltech

(simulated events)




Far detector site, September 12, 2010

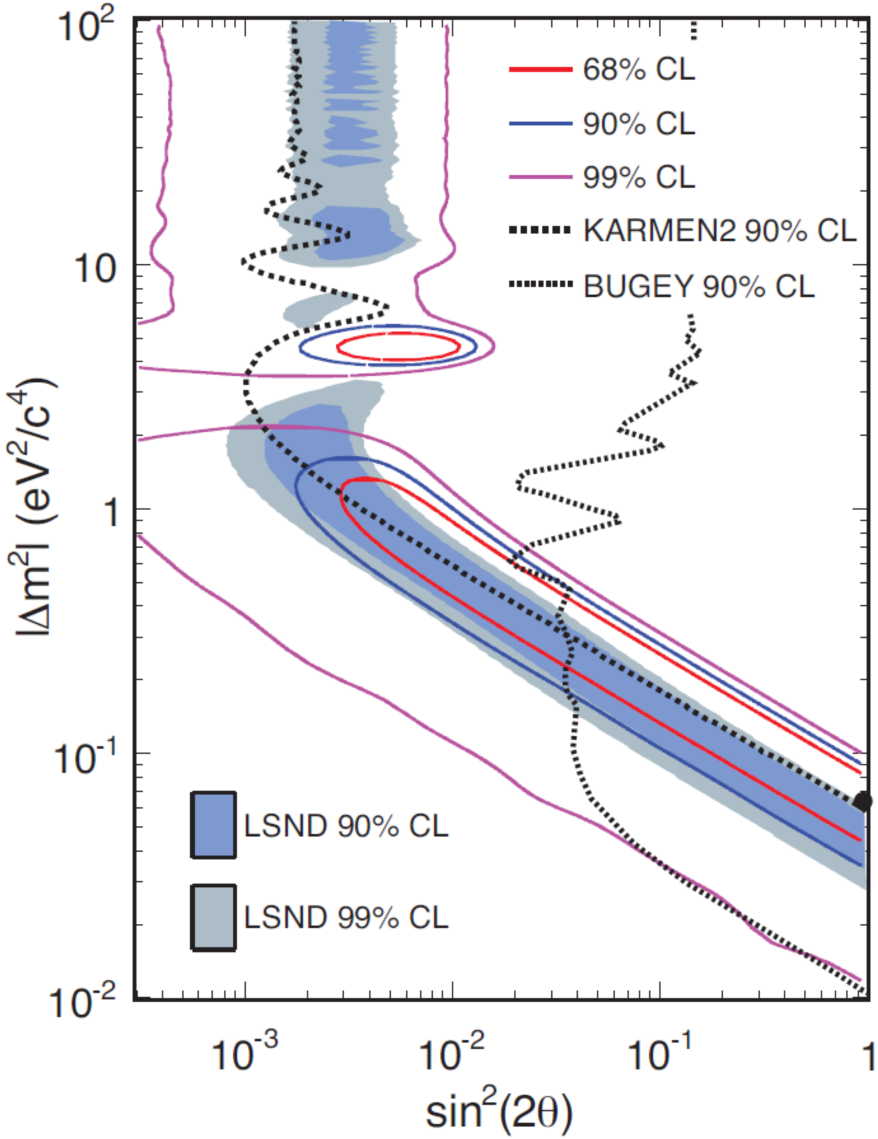

Far detector enclosure, October 7, 2010


Far detector enclosure, March 21, 2011


Near detector, October 13, 2010

Short-baseline $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ appearance with NuMI

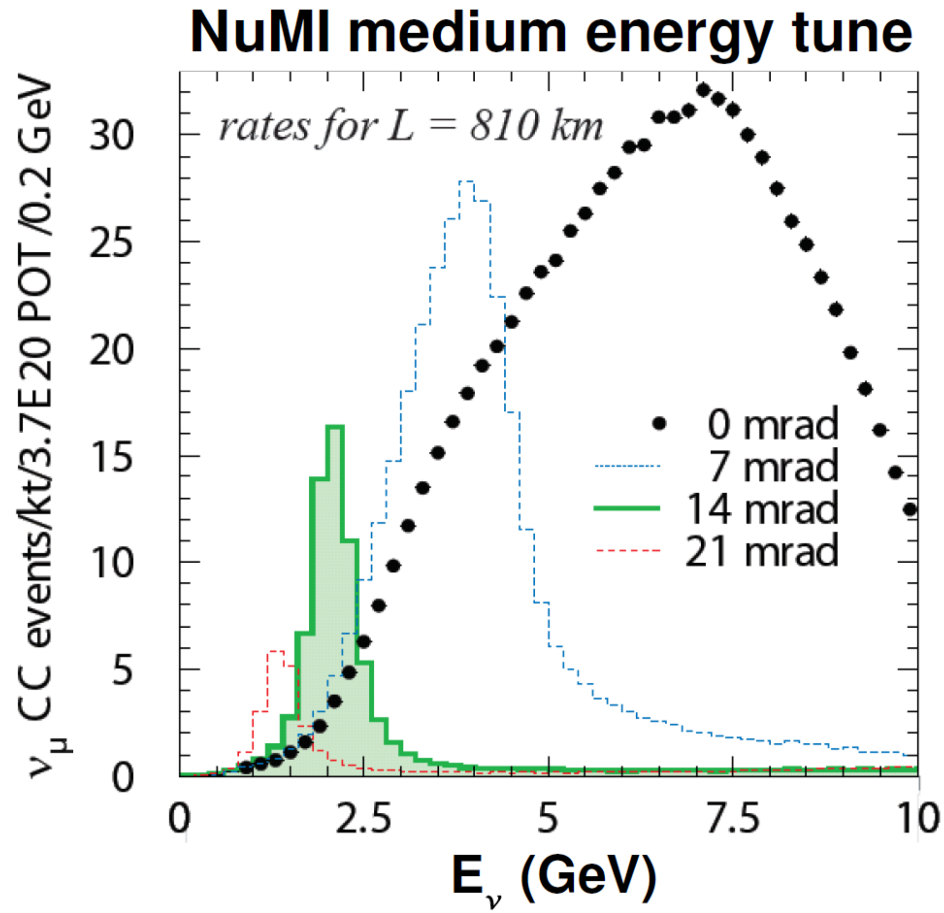
- Future **NuMI program** already includes ν **and** $\bar{\nu}$ **running**



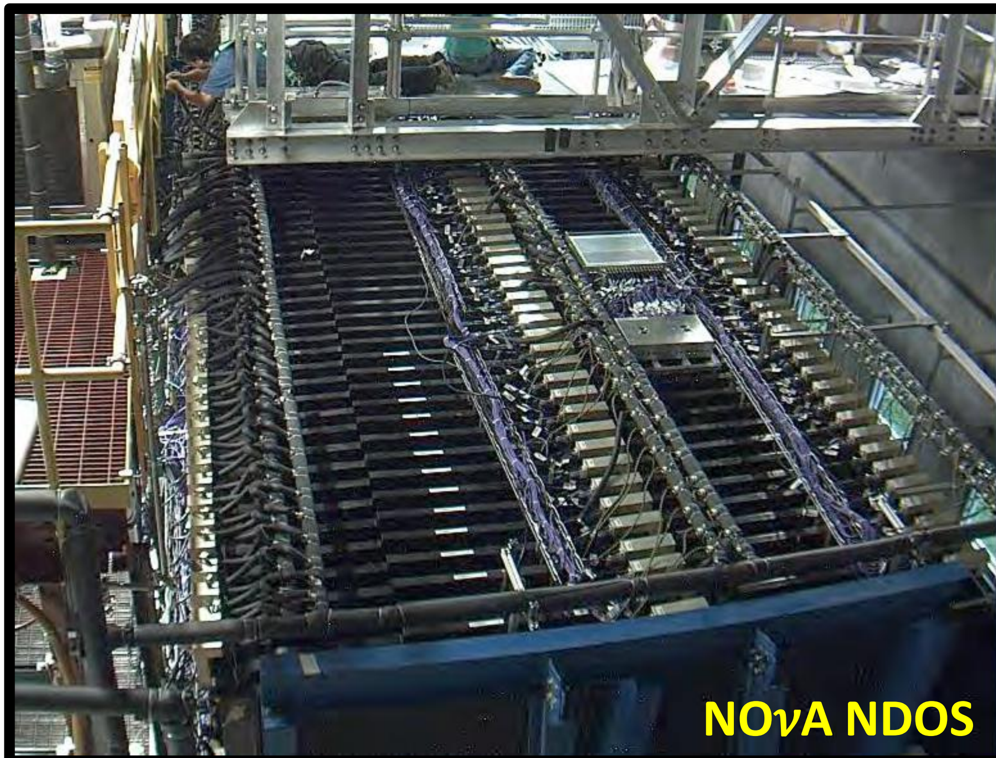
MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$
*PRL **105** 181801 (2010)*

Short-baseline $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ appearance with NuMI

- Future **NuMI program** already includes ν **and** $\bar{\nu}$ **running**
- **Off-axis flux** has small high-energy tail
  - ⇨ *reduction in NC background*



Short-baseline $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ appearance with NuMI



- Future **NuMI program** already includes ν **and** $\bar{\nu}$ **running**

- **Off-axis flux** has small high-energy tail
  ⇨ *reduction in NC background*

- NOνA intends to build a new near detector
  ⇨ *NDOS will become* ***free***

And, ***NDOS design*** *is aimed at* ***electron (anti)neutrino searches***

$\Delta m^2 \sim$ few eV^2

and

$E_\nu \sim 2$ GeV

$\Downarrow$

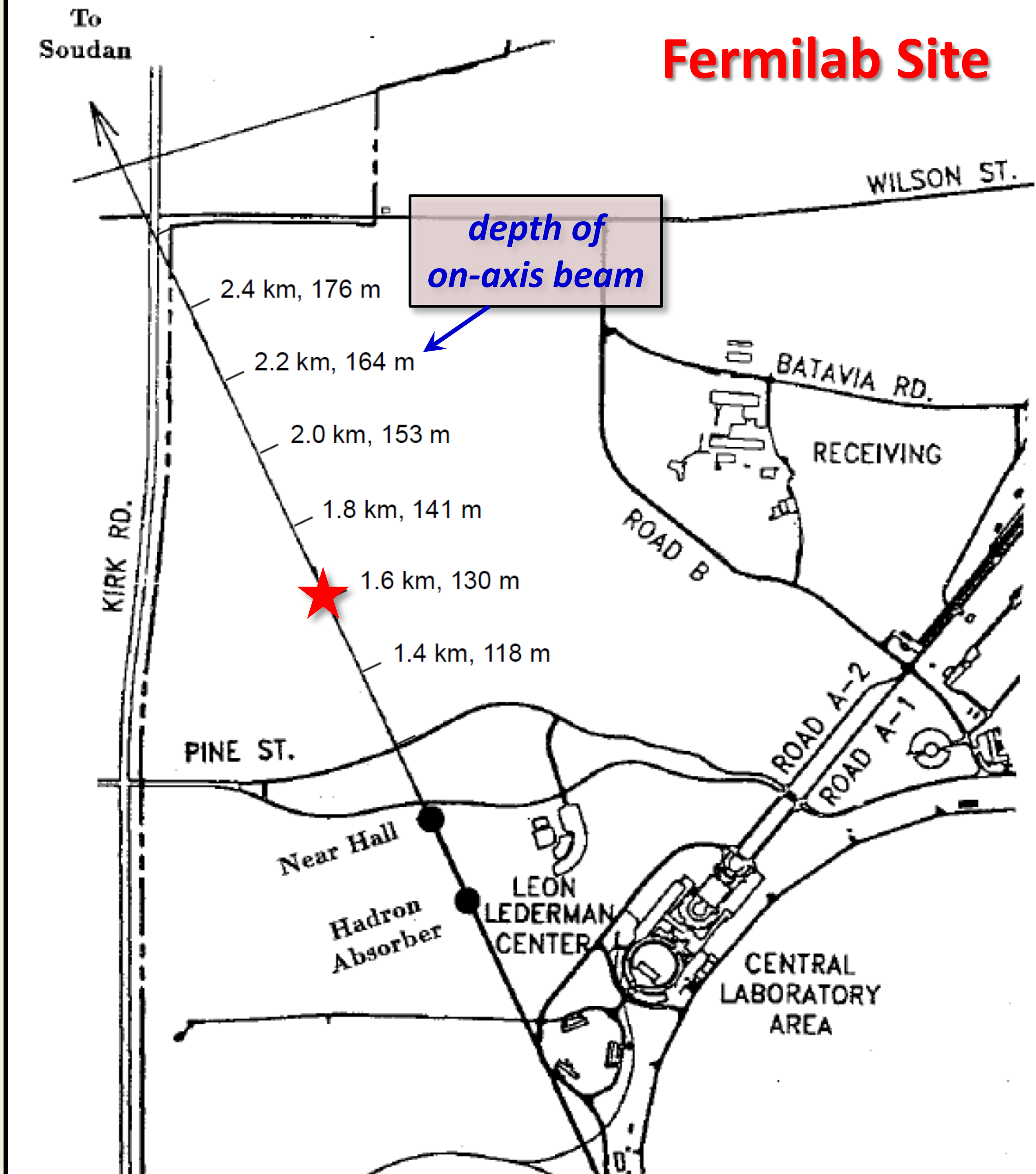
$L \sim 1$ to 2 km

Nominal placement:

1.6 km, 14 mrad

(110 m deep)

Fermilab Site



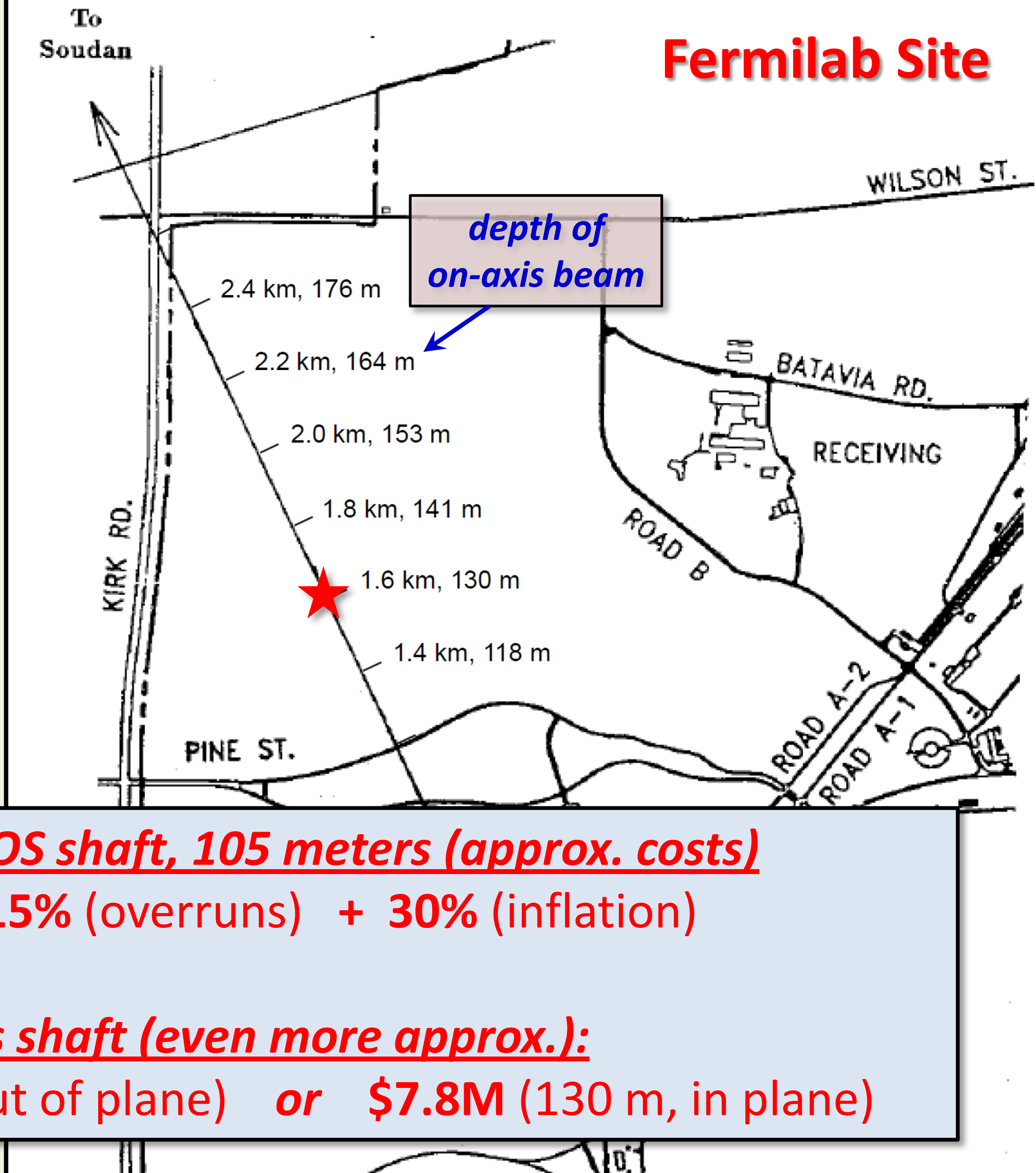
$\Delta m^2 \sim$ **few eV^2**

and

$E_\nu \sim$ **2 GeV**

$\Downarrow$

$L \sim$ 1 to 2 km



Nominal placement:

1.6 km, 14 mrad

(110 m deep)

NuMI/MINOS shaft, 105 meters (approx. costs)

\$4M + 15% (overruns) **+ 30%** (inflation)

This shaft (even more approx.):

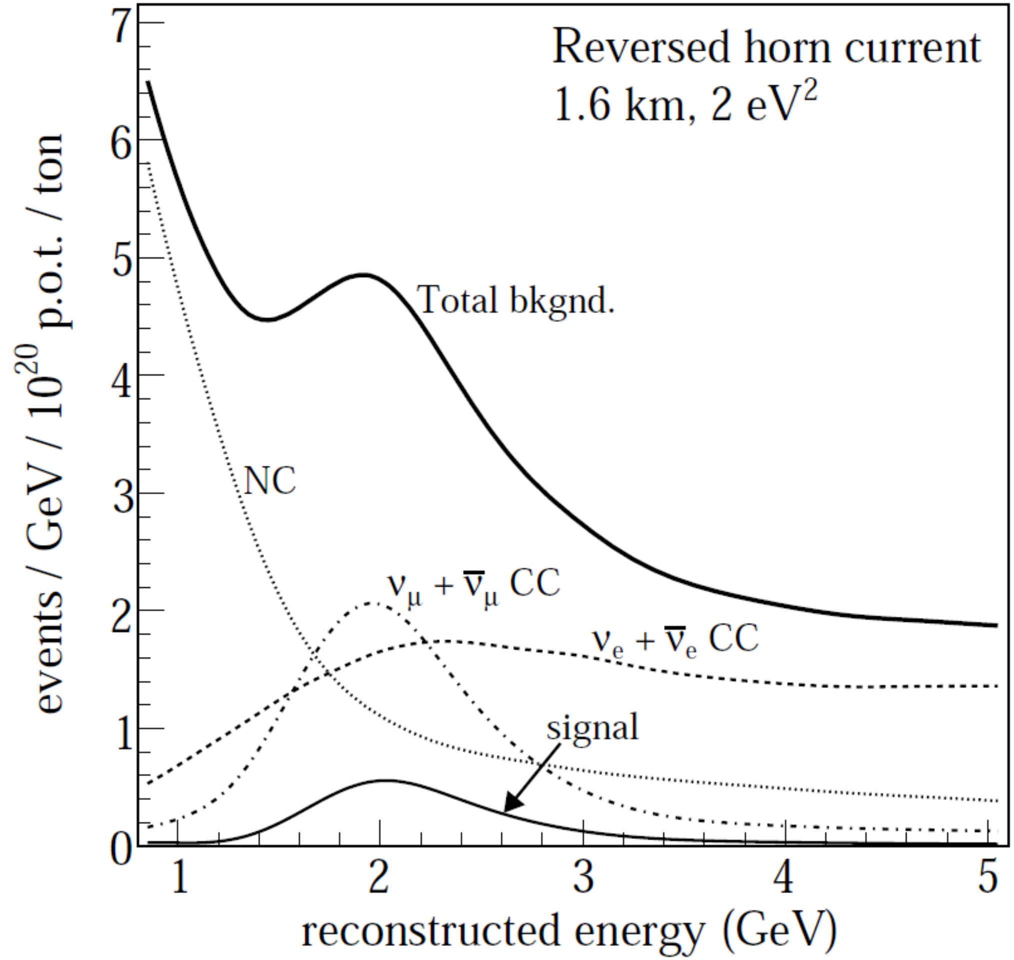
\$6.6M (110 m, out of plane) ***or*** **\$7.8M** (130 m, in plane)

Event spectra at 1.6 km

- Using **NOνA TDR efficiencies** (approx.; taken flat over *E*)

  ν_e CC: 30%
  ν_μ CC: 0.2%
  NC: 2%

  (NC efficiency does not include energy cut)



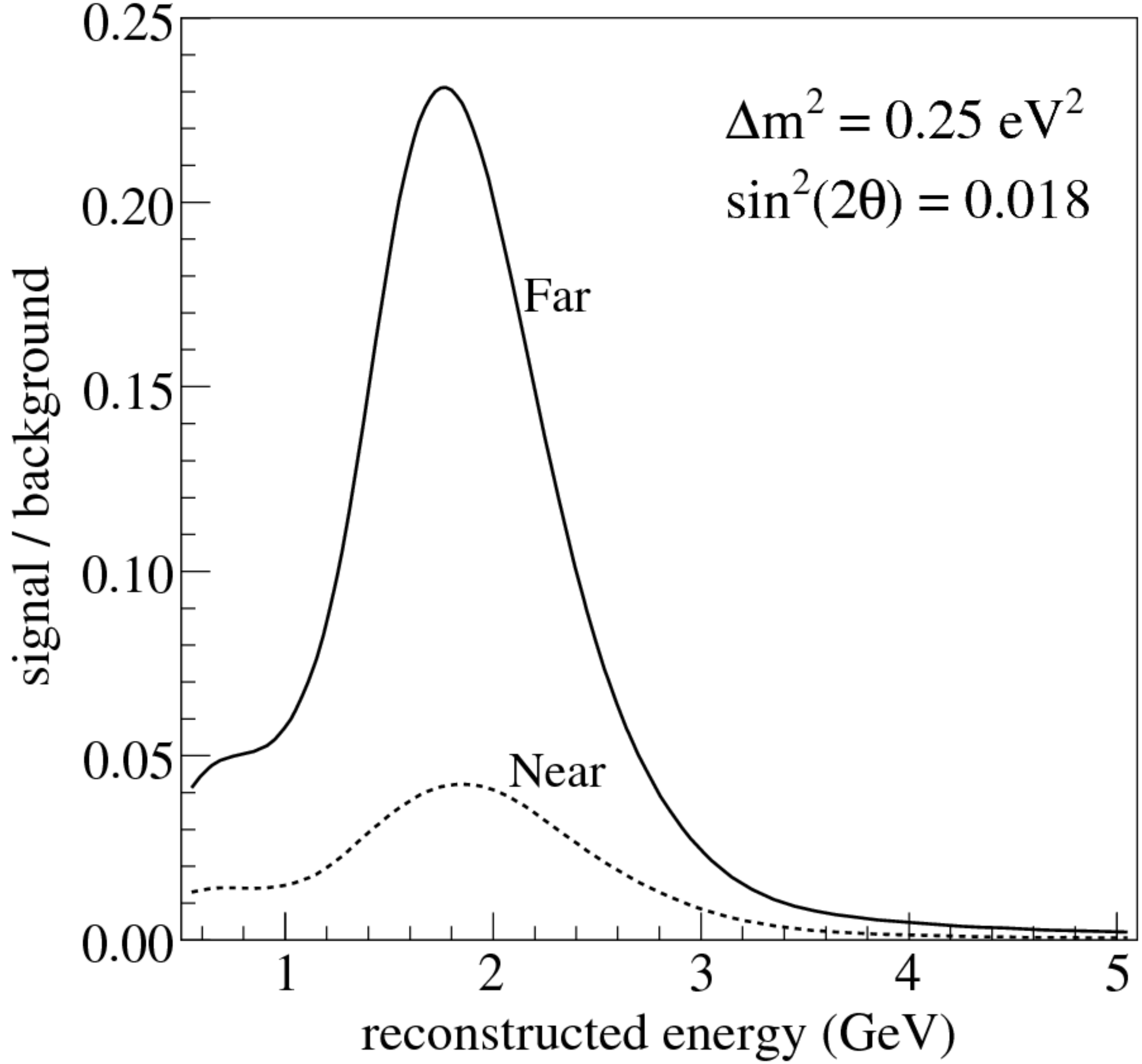
- **(6%) / (*E* / 2 GeV)$^{0.5}$** energy resolution applied

- LSND-like $\bar{\nu}_e$ appearance probability is *small*
  - $\bar{\nu}_\mu$ CC background particularly pesky given similar shape

For short-baseline osc.…

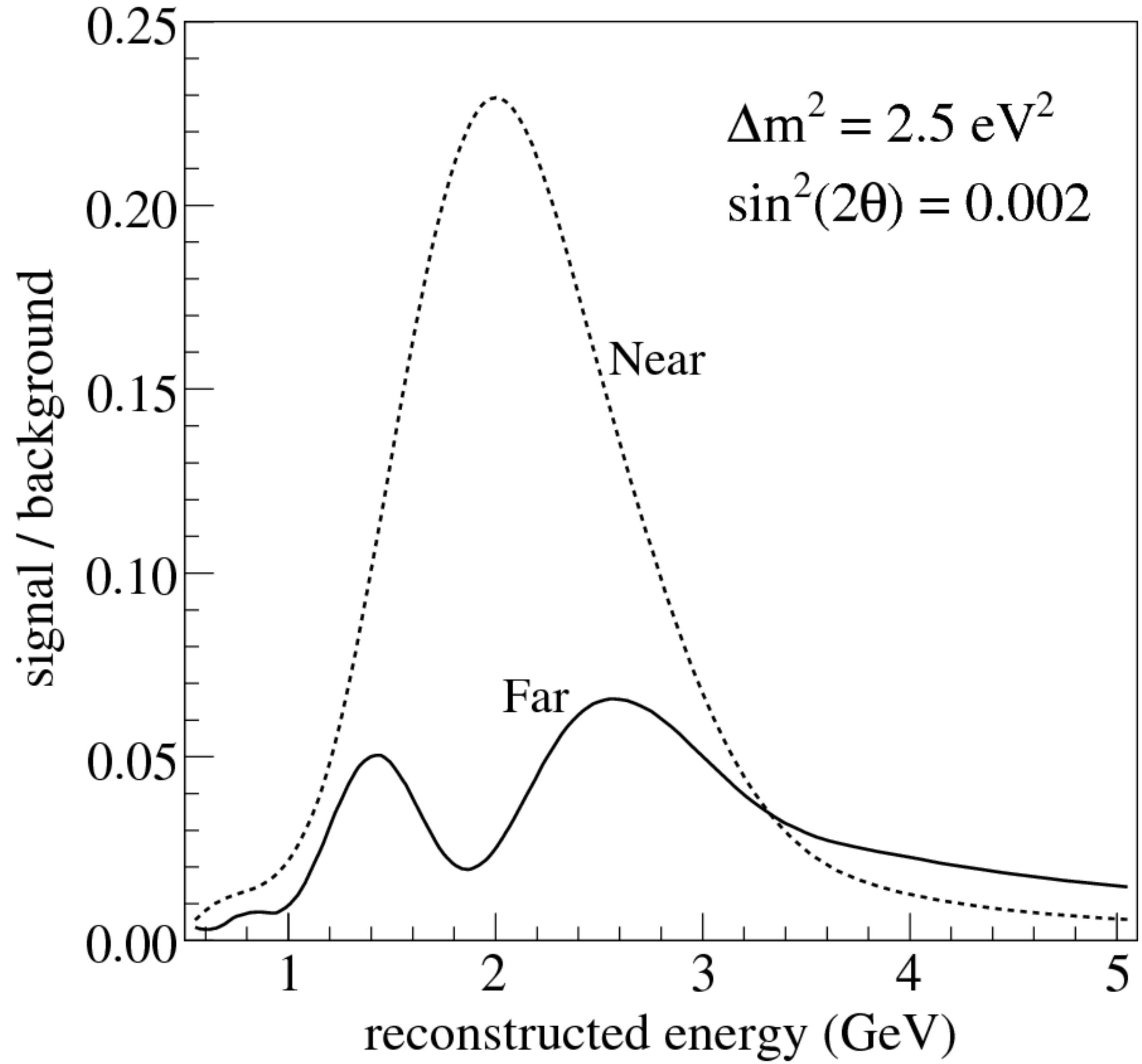
Far *and* ***Near*** *detectors take on* ***non-traditional roles****… (Next 3 pages)*

Signal in **Far** →



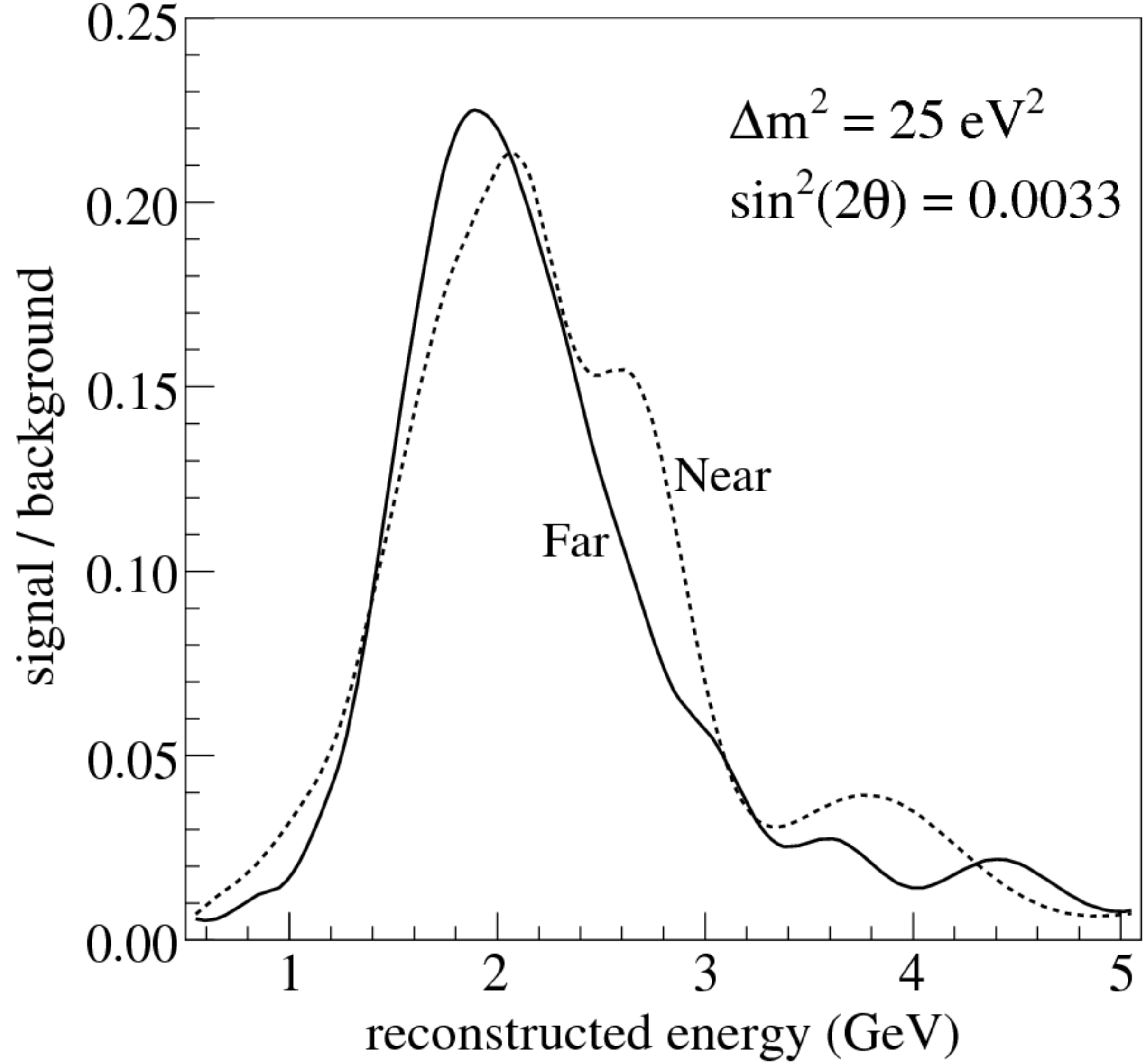
(Neutrino parent decay locations are folded in using Flugg-based NuMI beamline simulation)

Signal in **Near** →



(Neutrino parent decay locations are folded in using Flugg-based NuMI beamline simulation)

Signal in **Both** →



(Neutrino parent decay locations are folded in using Flugg-based NuMI beamline simulation)

Sensitivities

- Showing **sensitivities** on subsequent pages…
- Using a fit to the reconstructed energy spectrum (0.5 to 5.0 GeV)
- Assuming **3 years at 700 kW** (18×10^{20} p.o.t.) of **antineutrino running**
- **Systematic errors** are non-negligible!

Here are the errors taken →

(Labeled "optimistic" on the plots that follow)

Efficiency and E-scale errors are important when "Far" and "Near" see approximately the same signal

Relative normalization	**3%**
Relative energy scale	**2%**
Absolute energy scale	**5%**
ν_μ CC efficiency	**5%**
NC efficiency	**5%**
ν_e CC efficiency	**5%**
ν_μ right-sign flux norm.	**5%**
ν_μ wrong-sign flux norm.	**10%**
ν_e right-sign flux norm.	**5%**
ν_e wrong-sign flux norm.	**10%**

Some annotations…

Same detector technology at Far and Near site

Perhaps ambitious?

Assuming flux × XS constraints from (say) ν_μ CC channels

Relative normalization	3%
Relative energy scale	2%
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ν_e wrong-sign flux norm.	10%

Sensitivities

To begin:

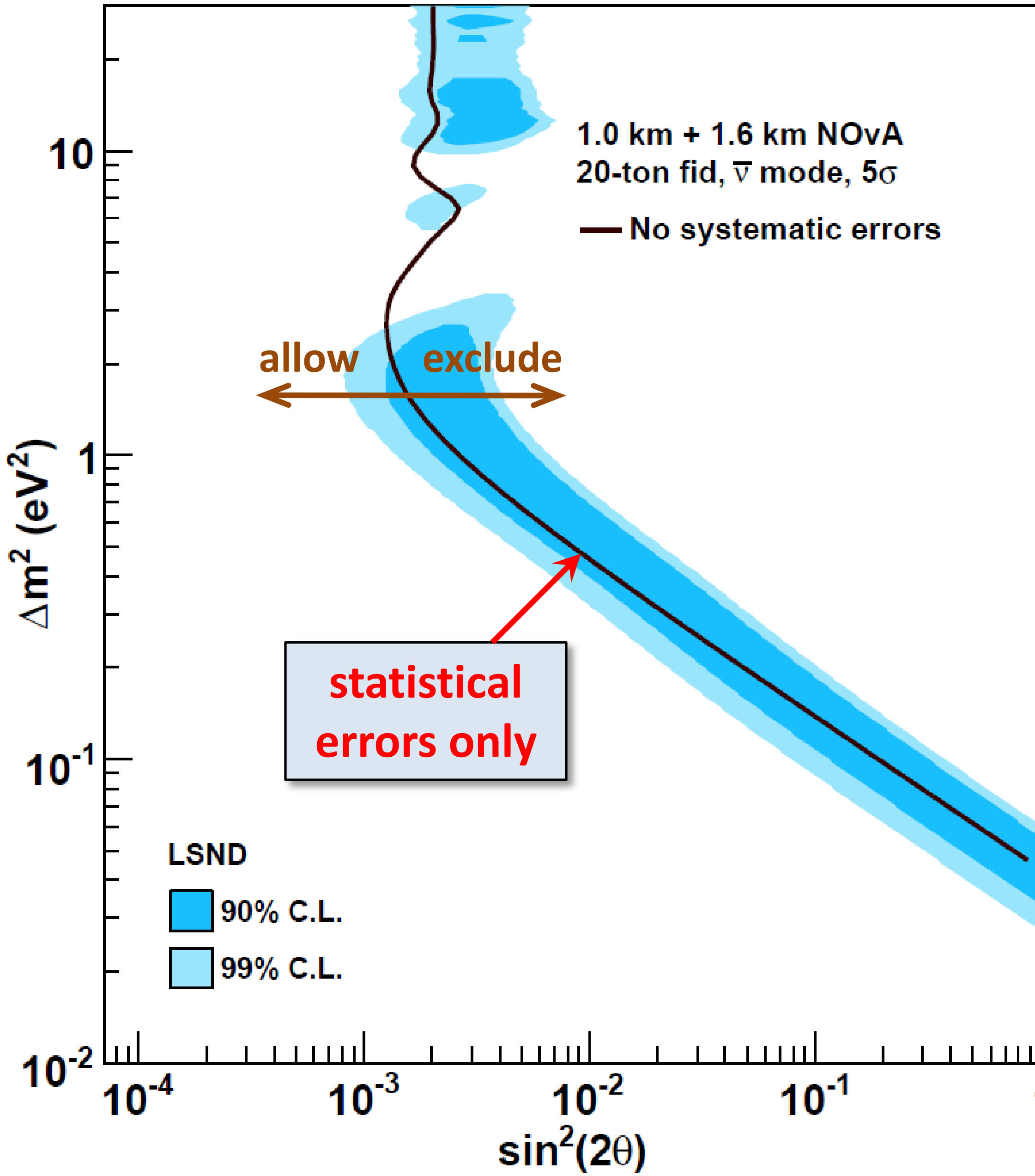
⇨ **20-ton fiducial mass NOνA detectors**

New ND at 1 km
Existing ND at 1.6 km

⇨ *1st:* **stat. errors only**

Note: **showing 5σ C.L. "2ν" $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ exclusion sensitivities throughout**

(Other existing measurements left off these figures for clarity.)



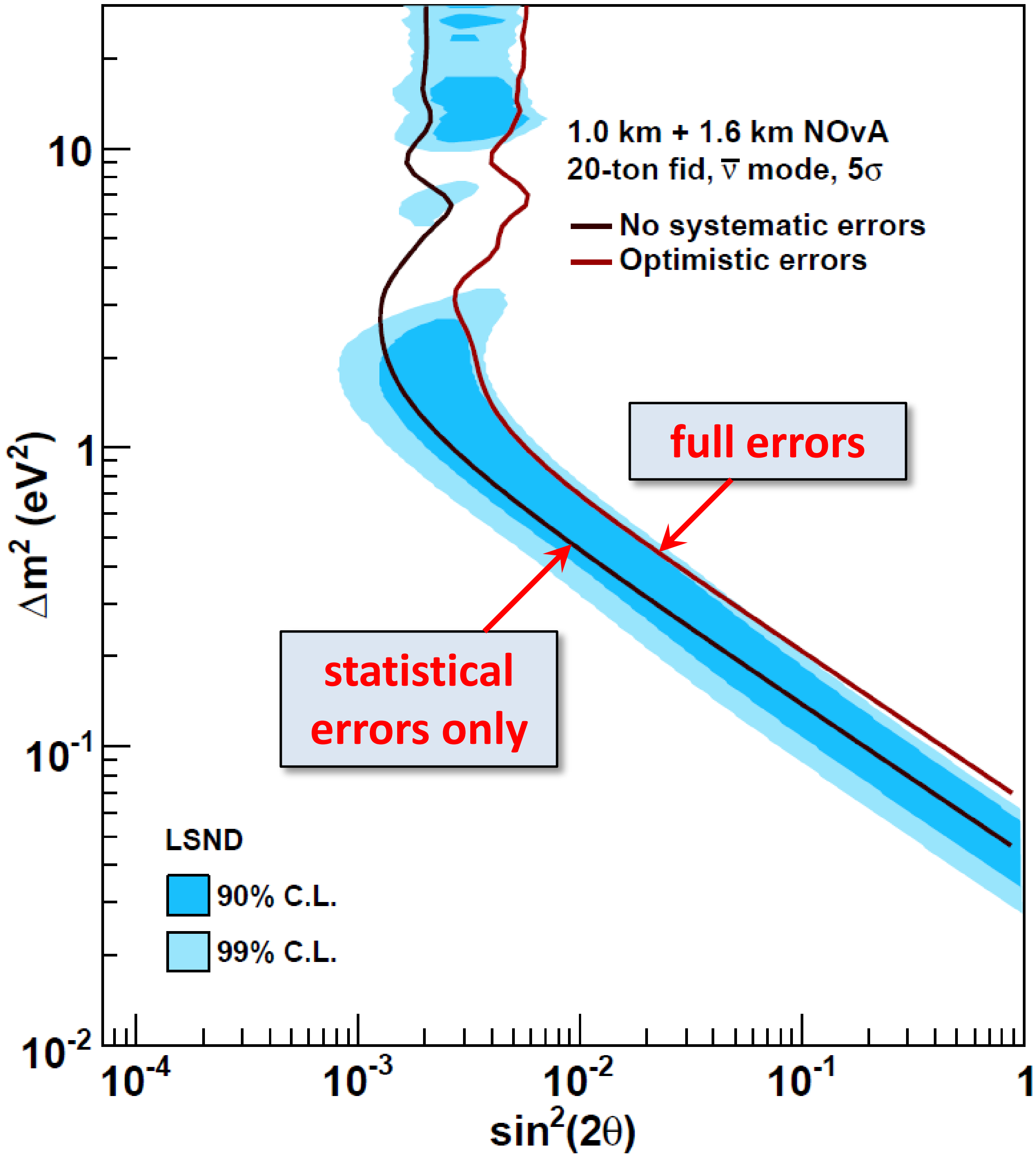
Sensitivities

To begin:

⇨ **20-ton fiducial mass NOνA detectors**

New ND at 1 km
Existing ND at 1.6 km

⇨ Now **with systematic errors**



Sensitivities

To begin:

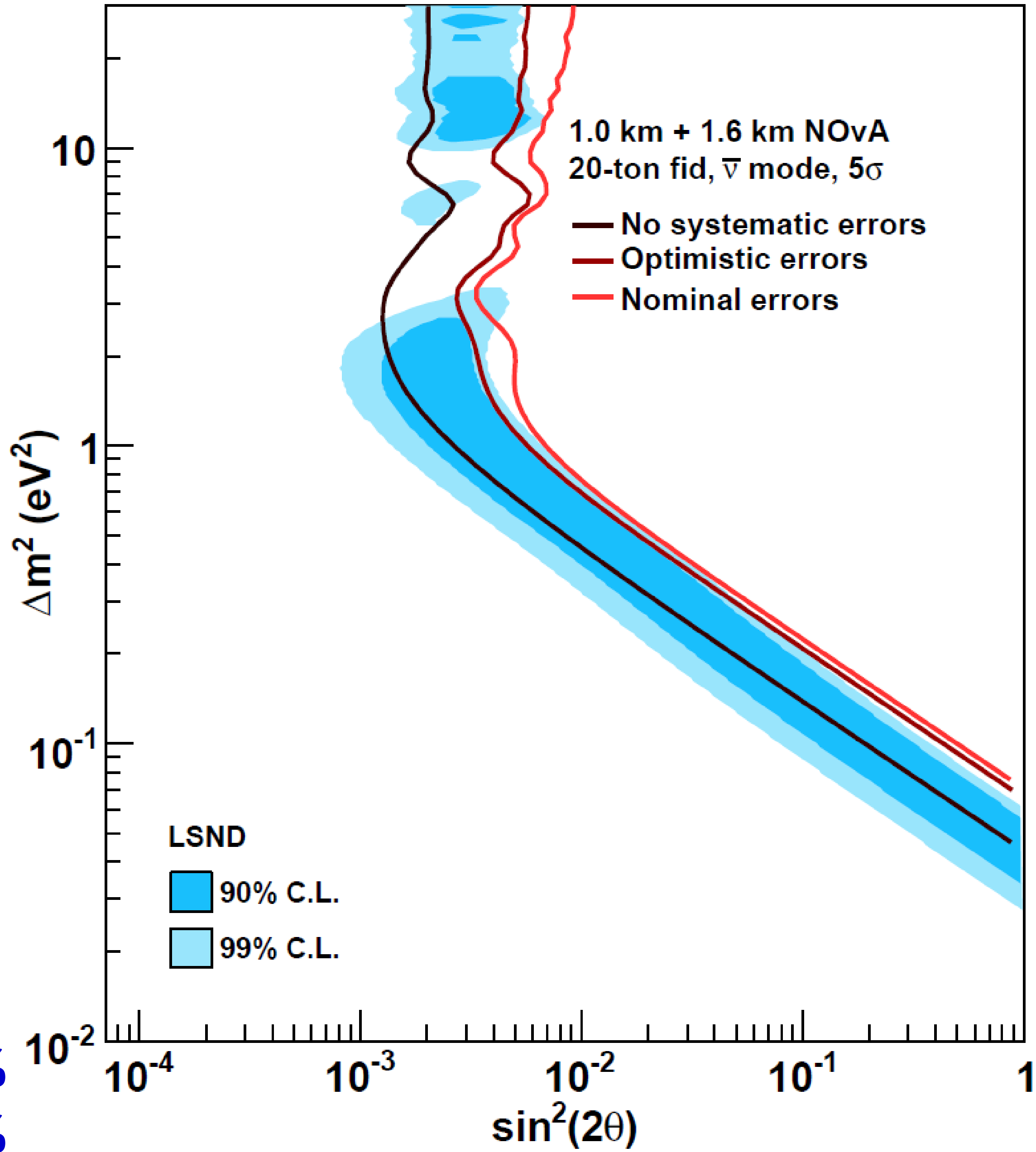
⇨ **20-ton fiducial mass NOνA detectors**

New ND at 1 km
Existing ND at 1.6 km

⇨ Now **with systematic errors**

⇨ Perhaps **safer error estimates:**

Abs. E:	**5% → 8%**
ν_μ CC eff:	**5% → 8%**
ν_e CC eff:	**5% → 10%**
RS flux:	**5% → 10%**



Sensitivities

To begin:

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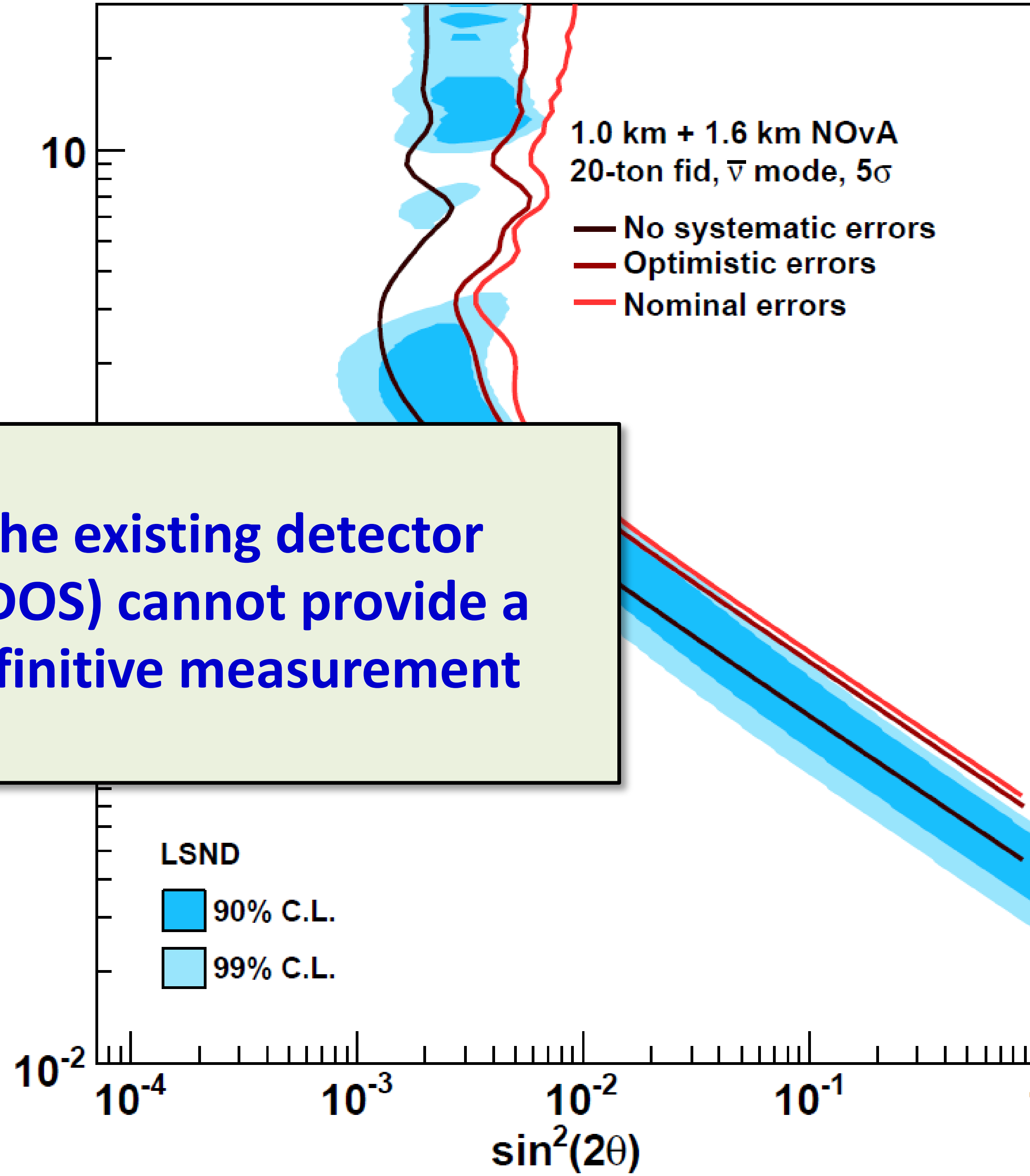


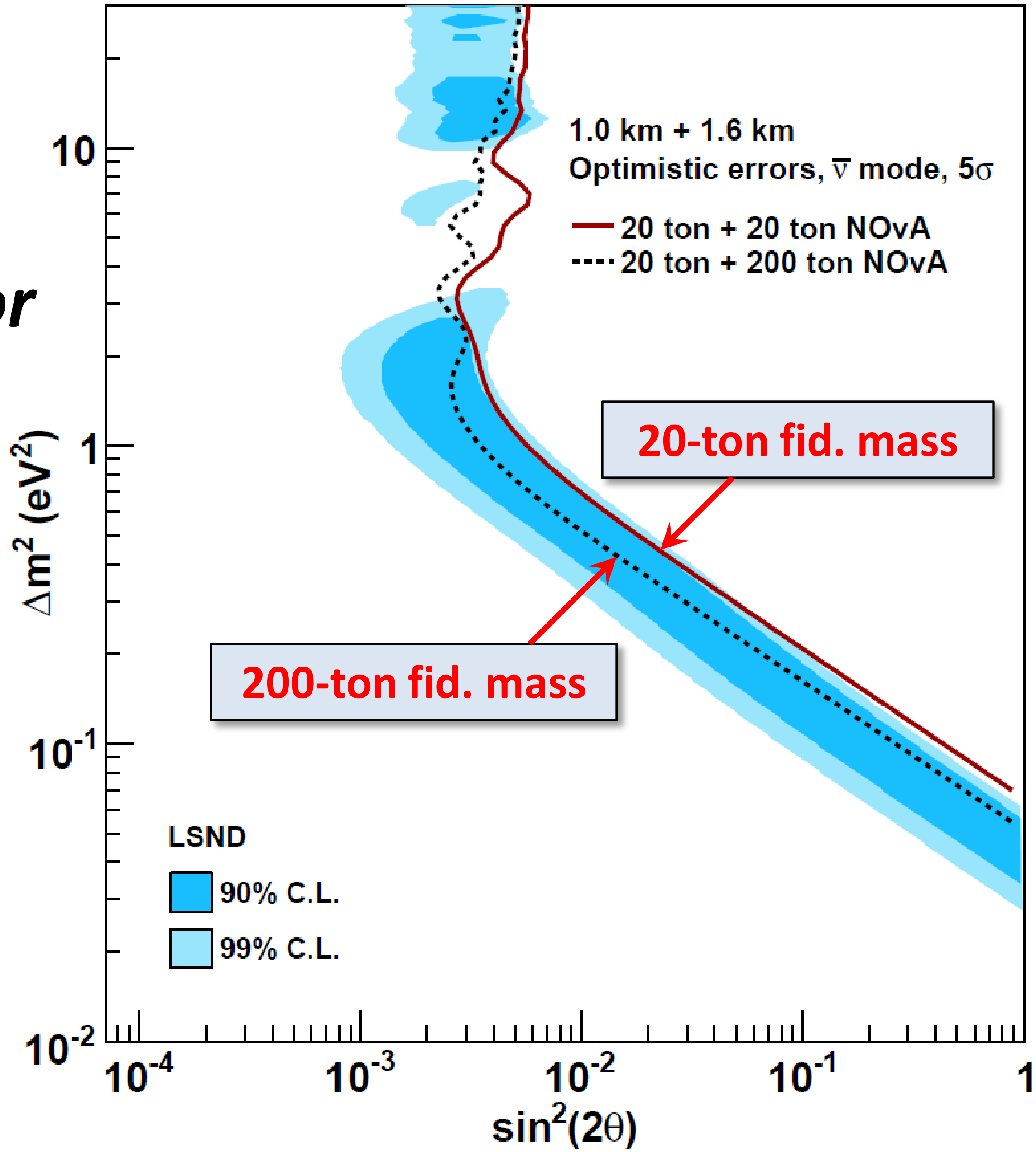
The existing detector (NDOS) cannot provide a definitive measurement

Sensitivities

Try a much bigger NOνA-style detector

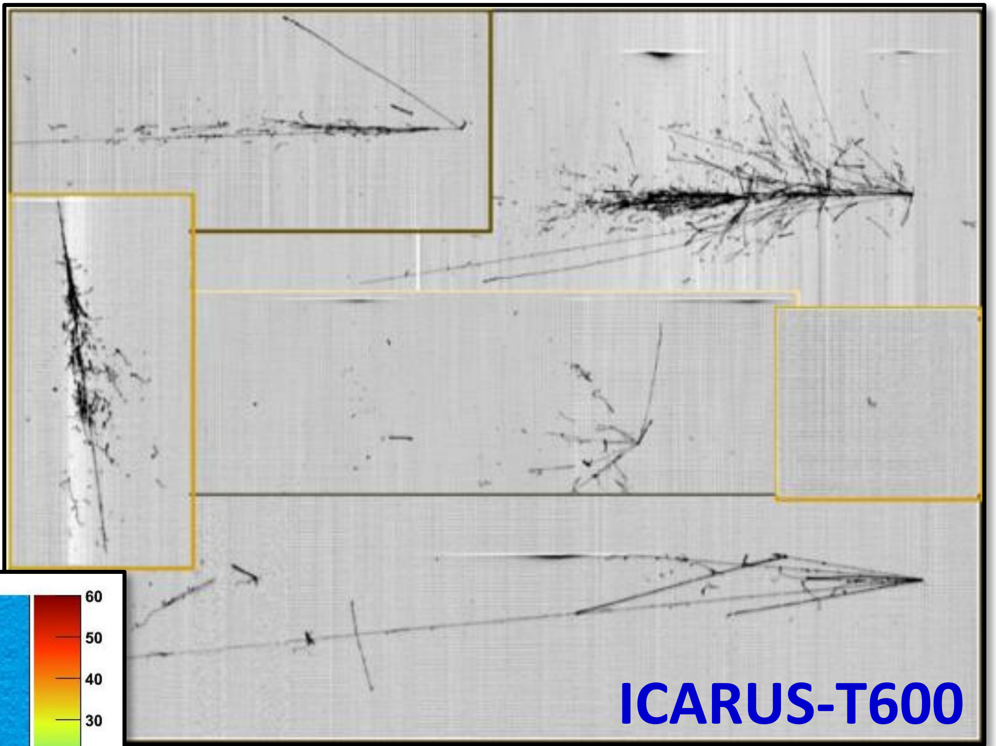
⇨ **200-ton fiducial mass at the far site**

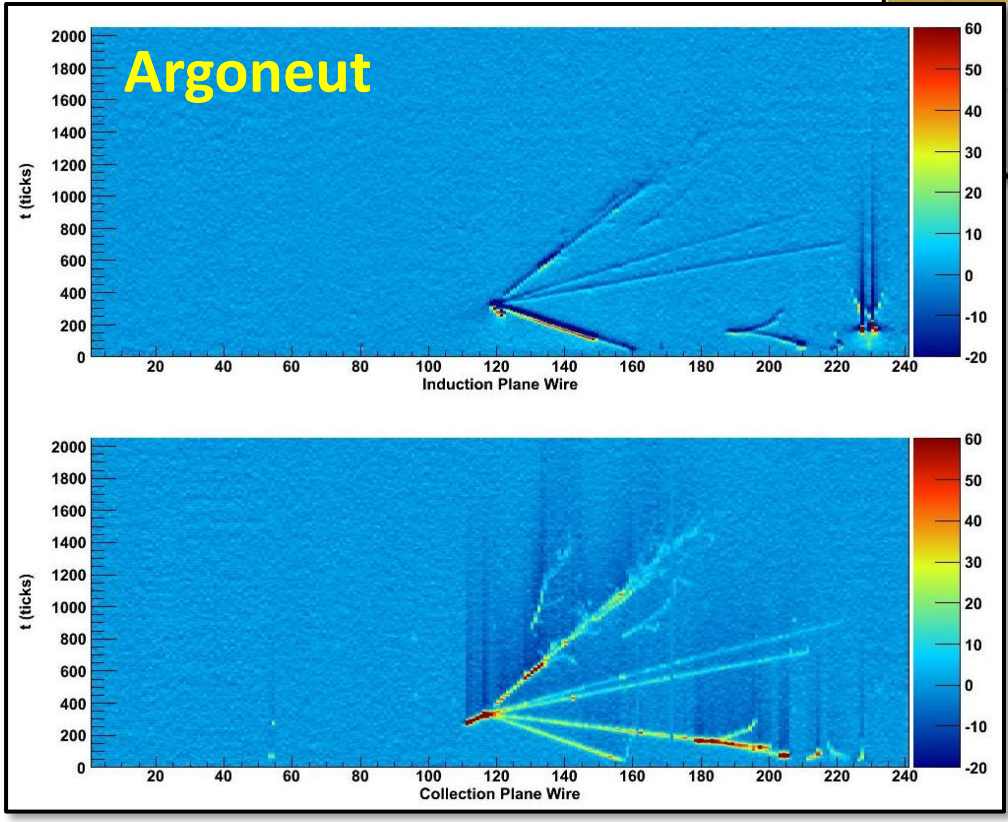
No longer have the benefit of using an existing detector...



LAr detectors?

As good as the NOvA ν_e identification may be…
LAr should do much better





Consider **LAr detectors** in the **NuMI off-axis beam**

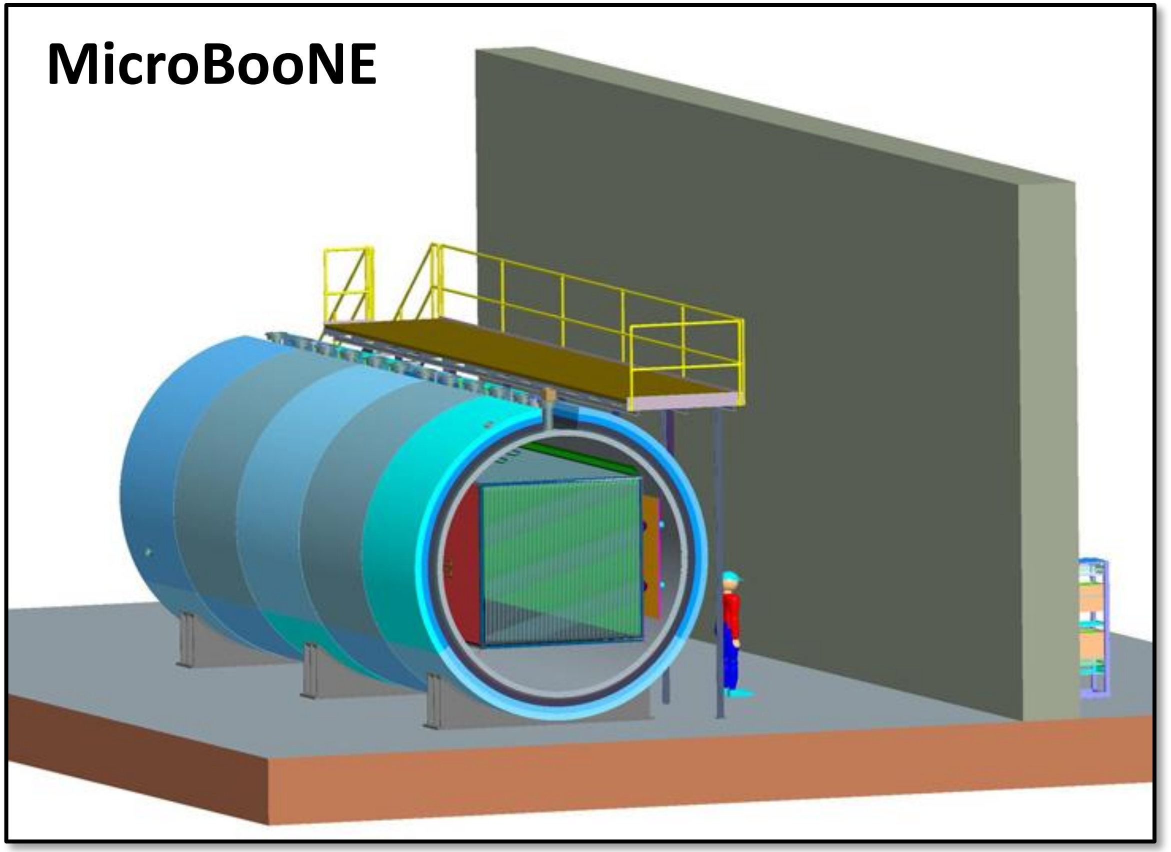
To begin (again):

⇨ **70-ton fiducial mass LAr detectors**

Same detector design at 1 km and 1.6 km

⇨ **MicroBooNE-scale**

⇨ Adds additional ND cavern ($5M?) + two new detectors (driving cost!)

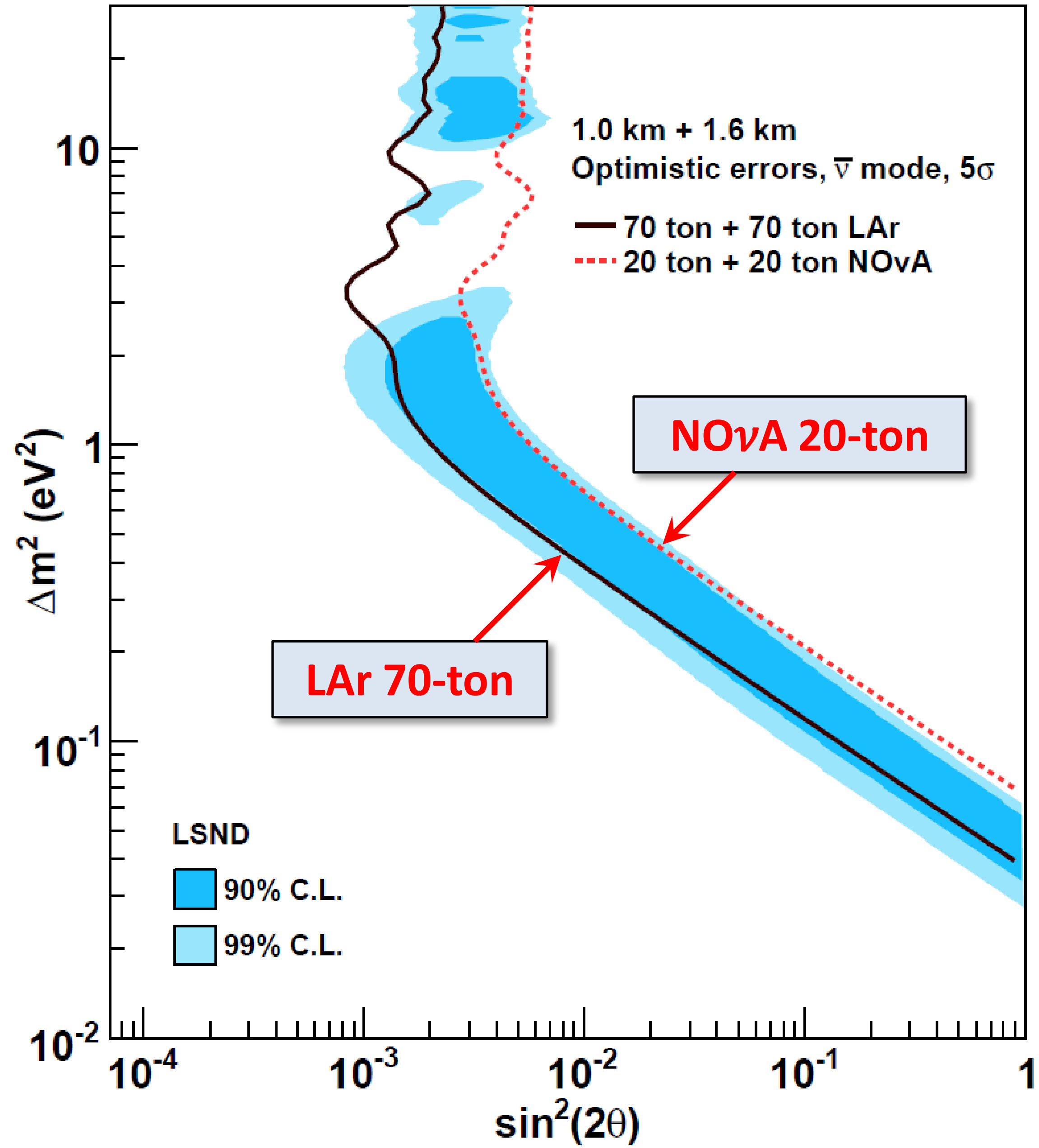


No good estimates of **LAr TPC selection efficiencies.** *Thus…*

Encapsulate the **LAr improvement** over NOνA-style detectors as an **increase in ν_e CC selection efficiency (30%→85%)**

…keeping background efficiencies the same

Marked improvement



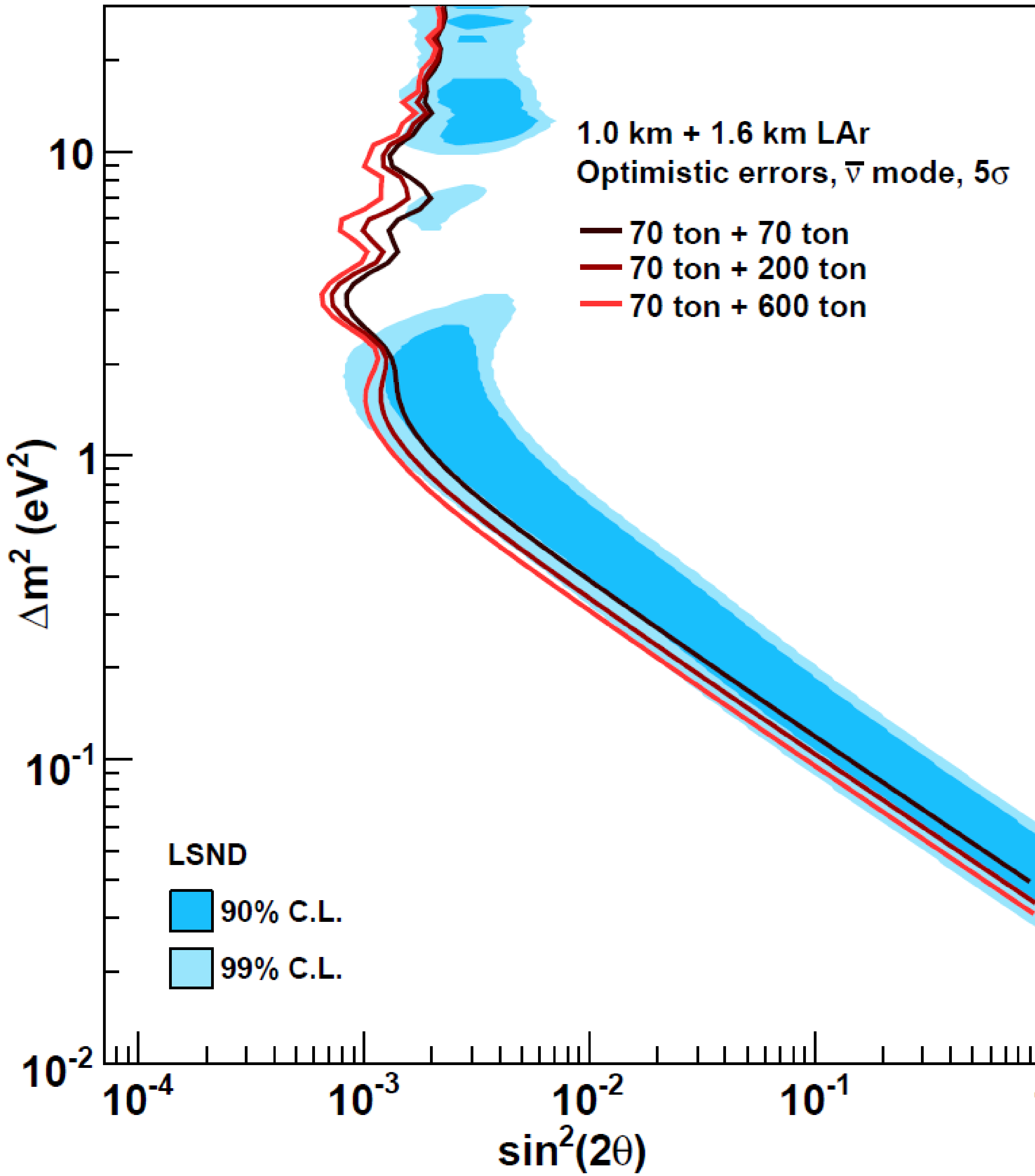
Marked improvement

Still systematics limited

A. 1 × μ-BooNE @ NuMI

B. 3 × μ-BooNE @ NuMI
1 × μ-BooNE @ Project-X

C. 9 × μ-BooNE @ NuMI
3 × μ-BooNE @ Project-X



Marked improvement

<u>*Still systematics limited*</u>

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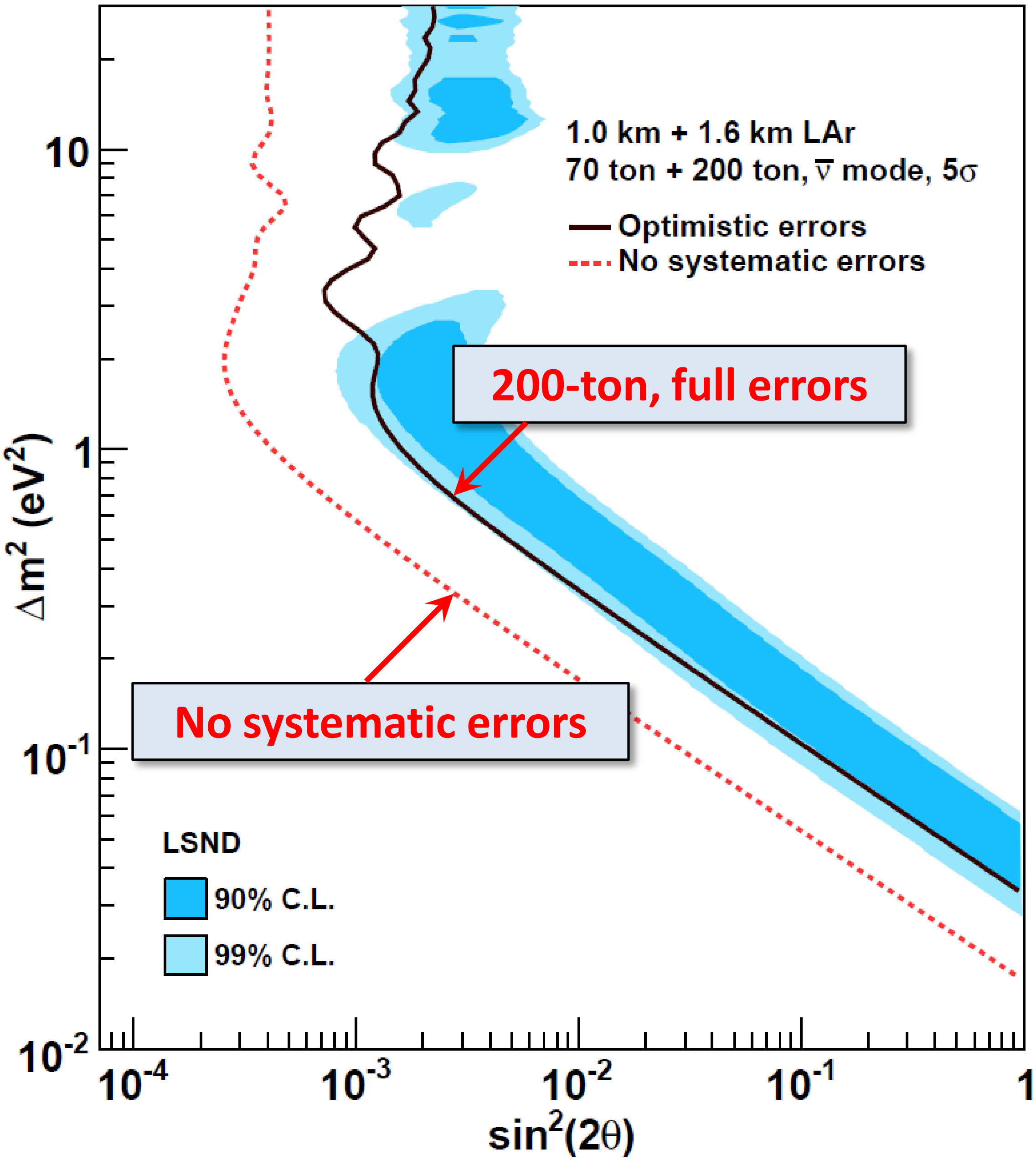
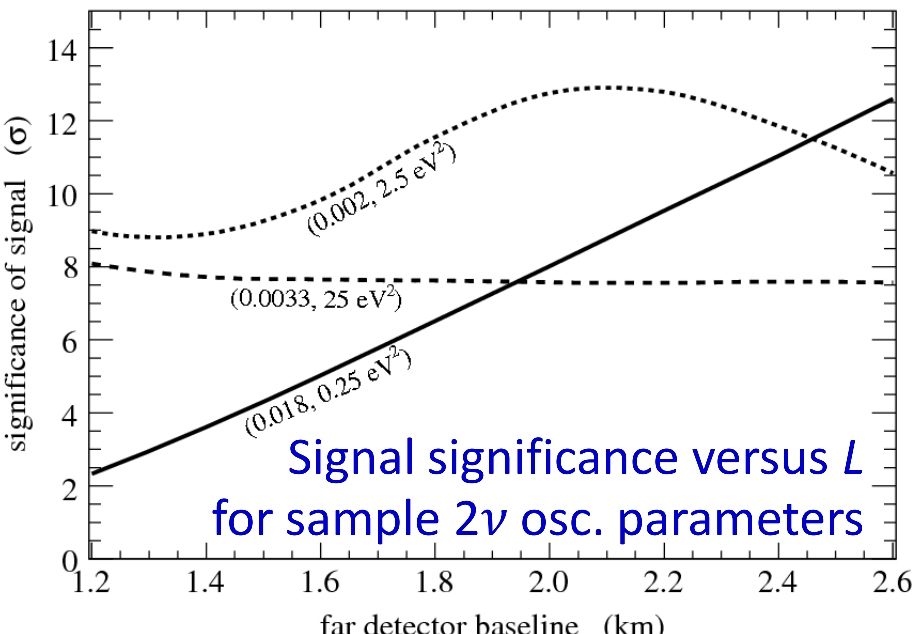
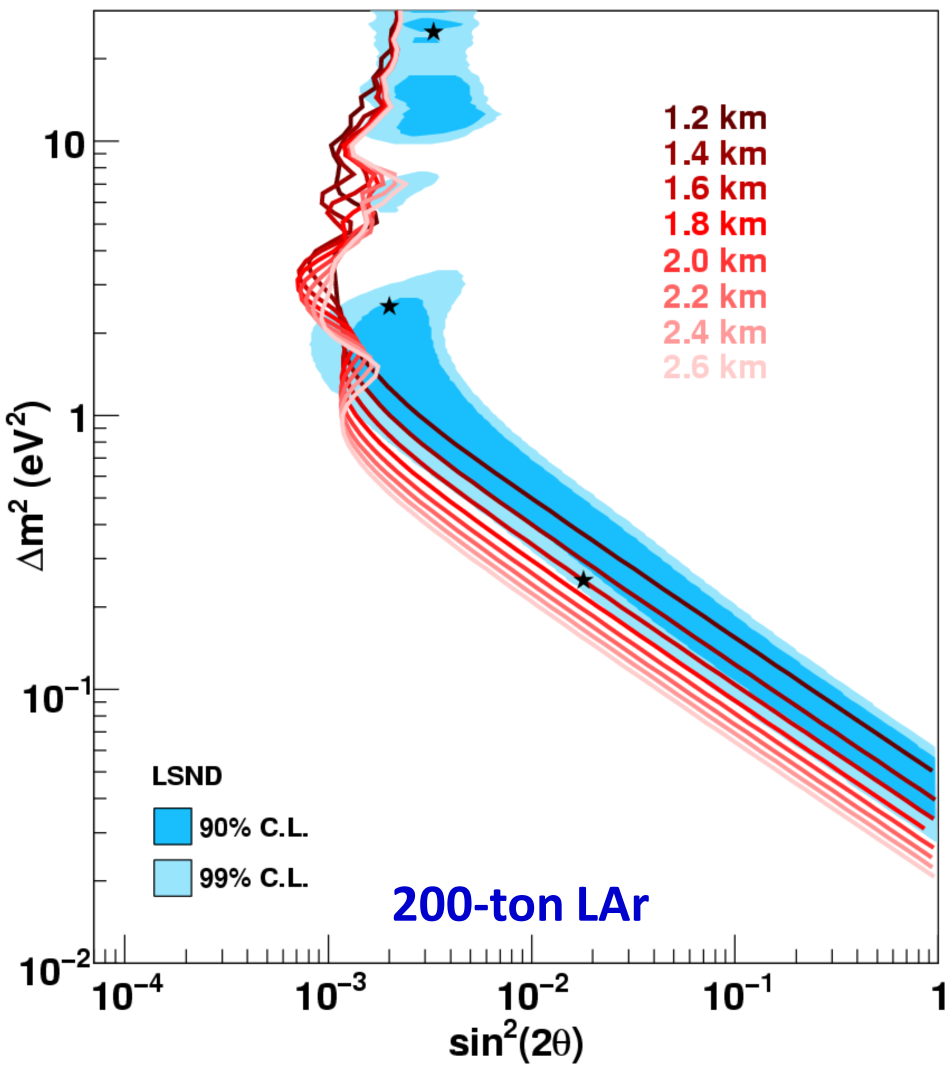


Quick note on baseline

- Have been using 1.6 km for FD
- **Best location** depends on:
  - → *the physics model (of course)*
  - → *your favorite parameters*
  - → *the dominant systematics*



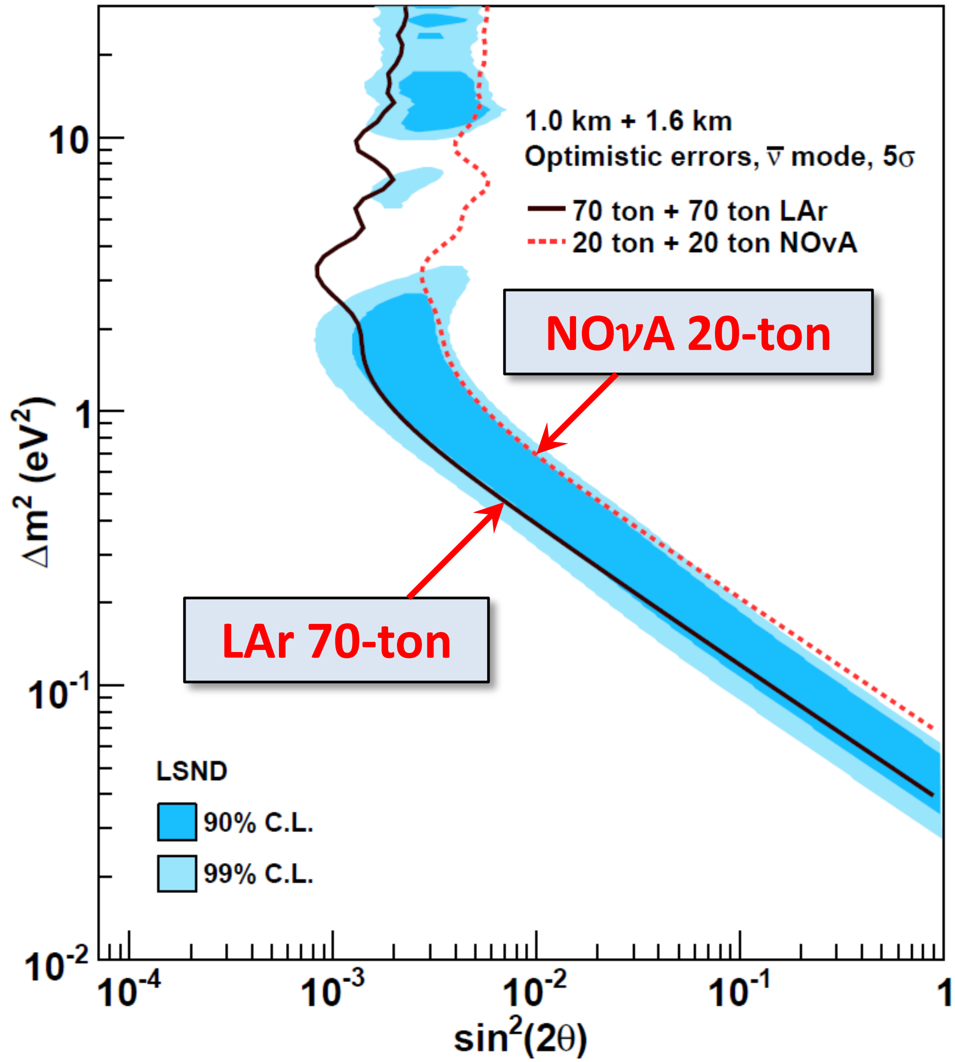


Summary (p. 1)

- Placing the (existing) **NOνA NDOS** at a 2-km baseline in the **NuMI off-axis beam** could (*in principle*) allow one to **constrain LSND-like $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$**

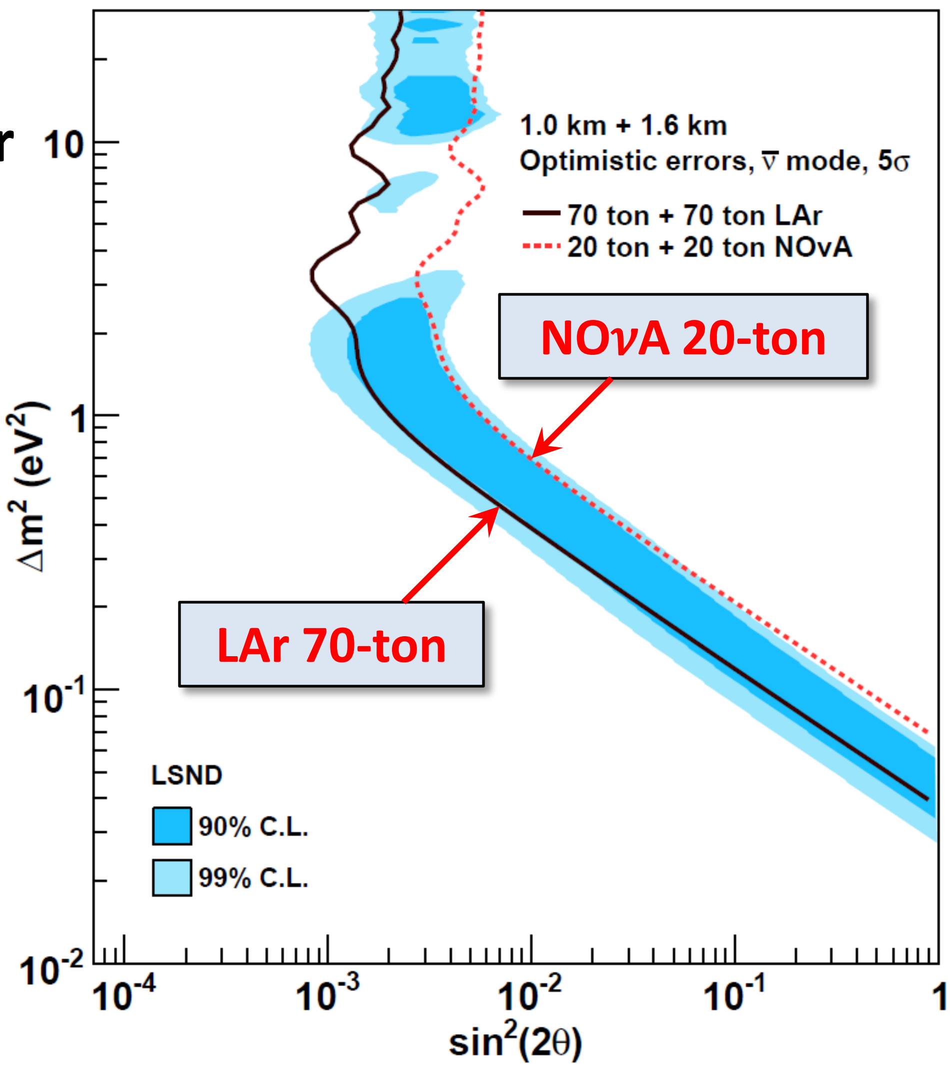
- **But!** Sensitivity appears grossly insufficient.

- *However…*



Summary (p. 2)

- A MicroBooNE-scale **LAr detector could work** (!), especially **if LAr efficiencies end up better** than the estimates used here.
- More sophisticated LAr **efficiency and error estimates** needed
- A companion LAr detector would potentially benefit NOνA *(e.g., understanding the "deep" backgrounds)*



Promising reach!

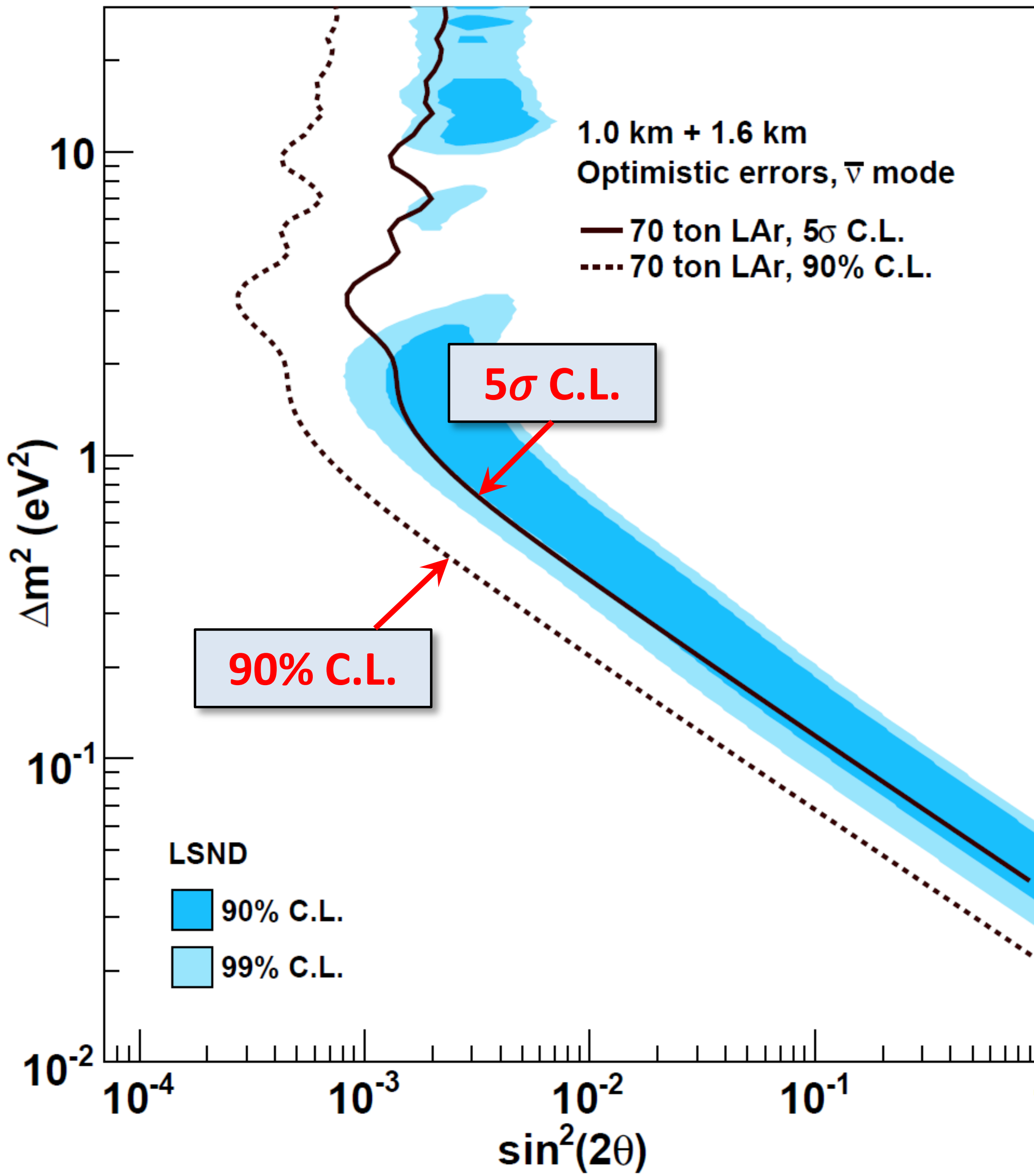
(Remember: 5σ C.L. exclusion contours shown)

Paper in prep.

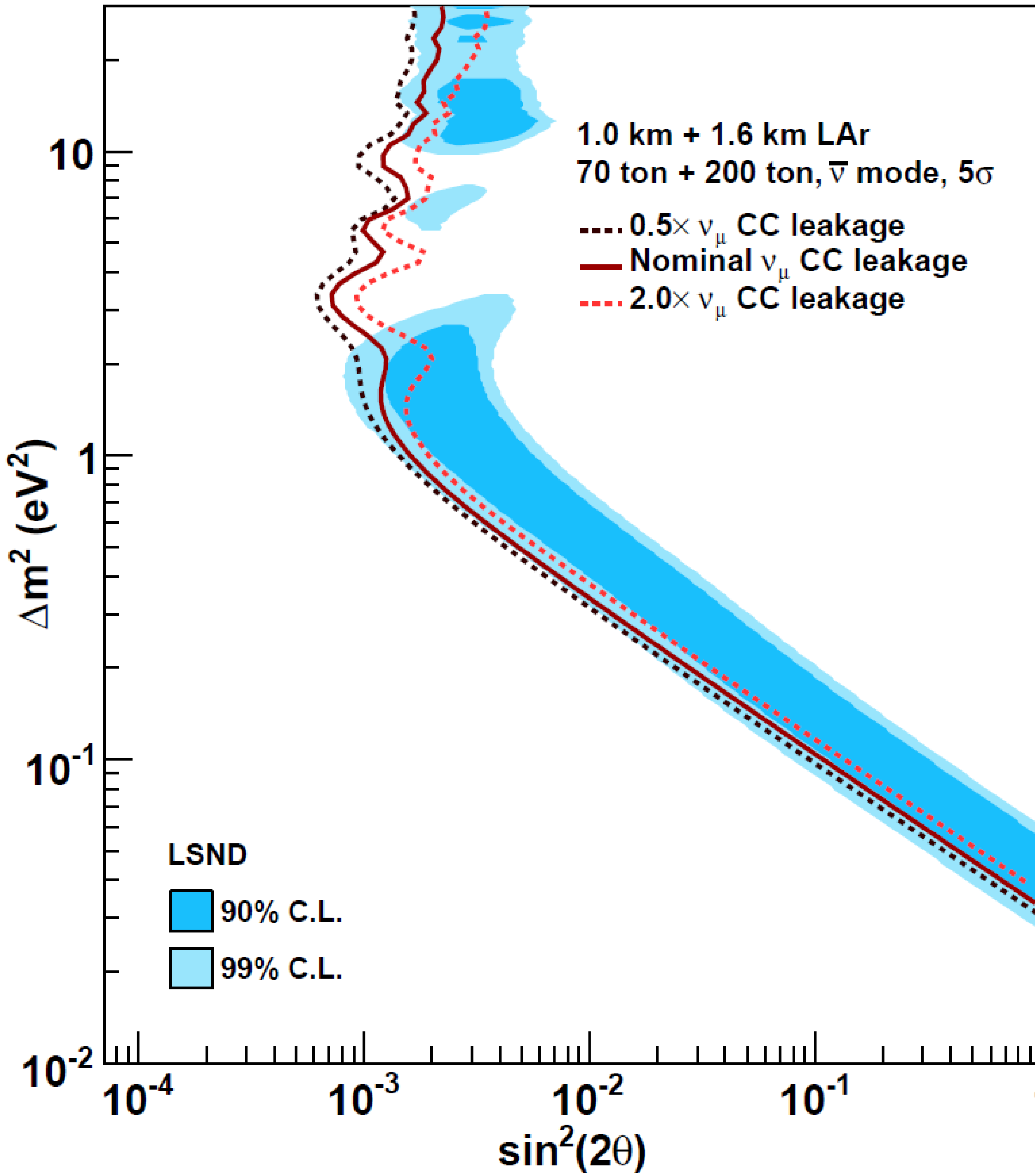
Backups

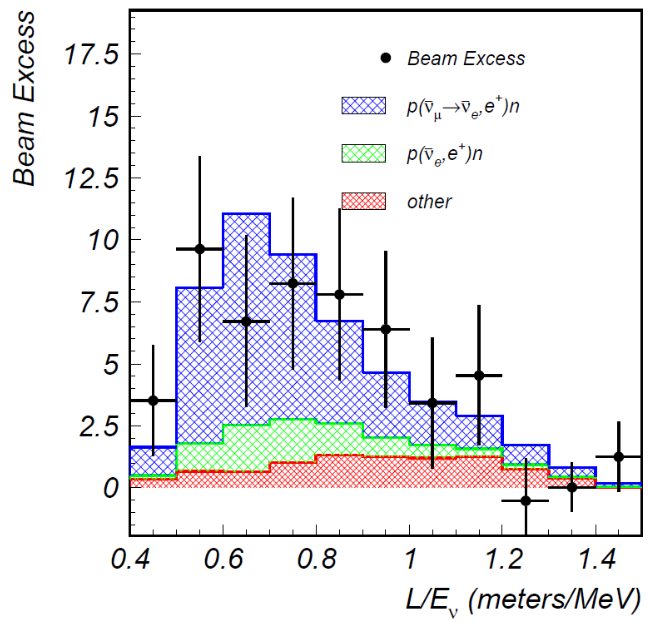
5σ and **90% C.L.** curves together

(70-ton LAr)



Varying ν_μ CC efficiency…





(plots here for reference)